WIRELESS ENGINEER

THE JOURNAL OF RADIO RESEARCH & PROGRESS

NOVEMBER 1954

VOL. 31 No. 11 THREE SHILLINGS AND SIXPENCE

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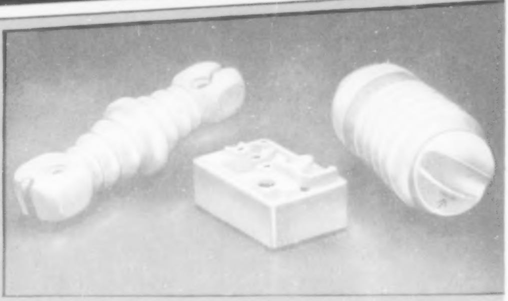

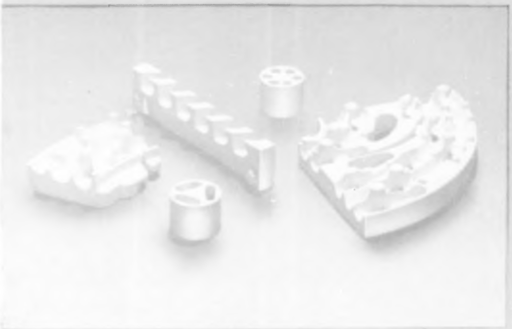

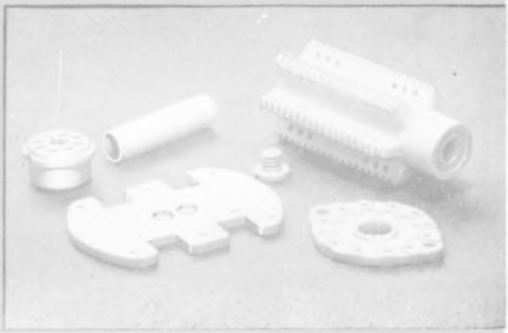

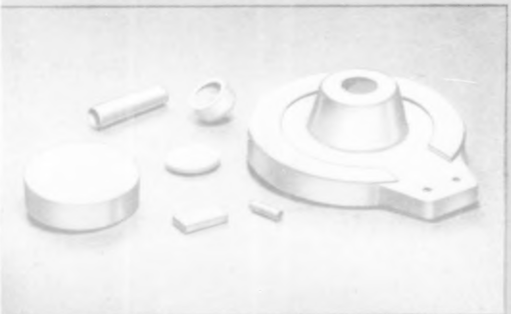

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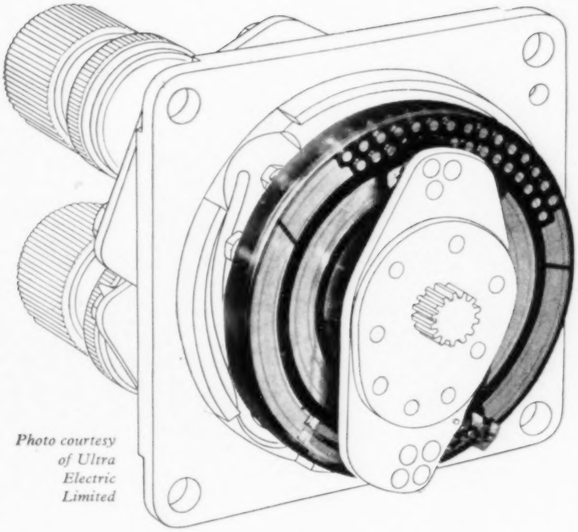

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This selector unit (part of the Ultra Jet Pipe Temperature Control System) controls the temperature of the exhaust gases of a turbo-jet aero-engine.

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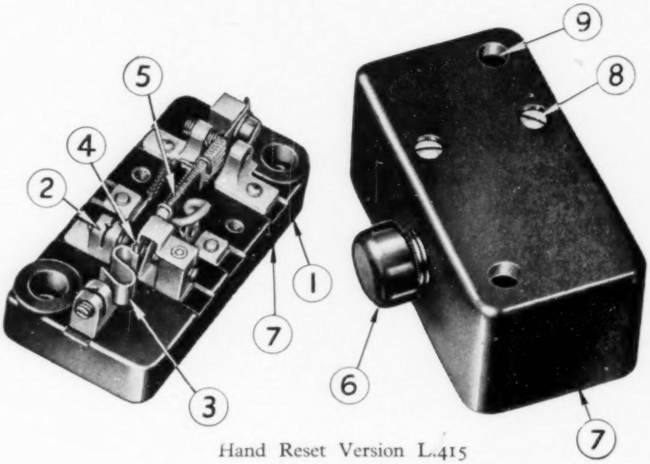
.. show why "BELLING LEE" THERMAL DELAY SWITCHES *are best in the long run*



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Automatic Reset Type L.413
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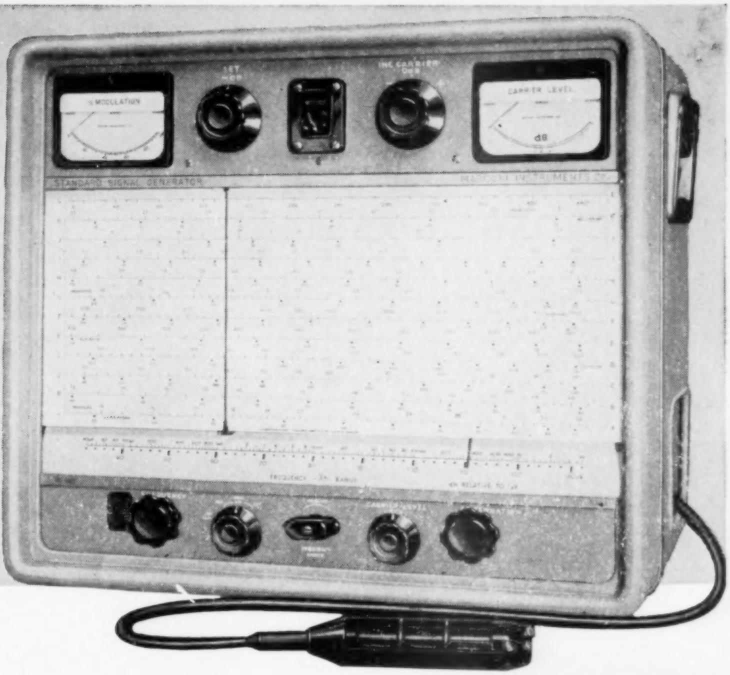

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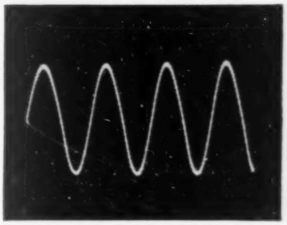
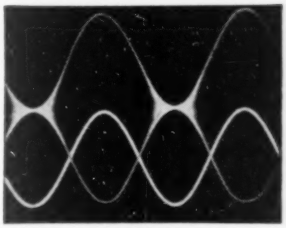


15 kc/s Unmodulated Carrier showing good waveform.



320 kc/s Carrier modulated at 400 cps—audio source on lower trace shows fidelity.

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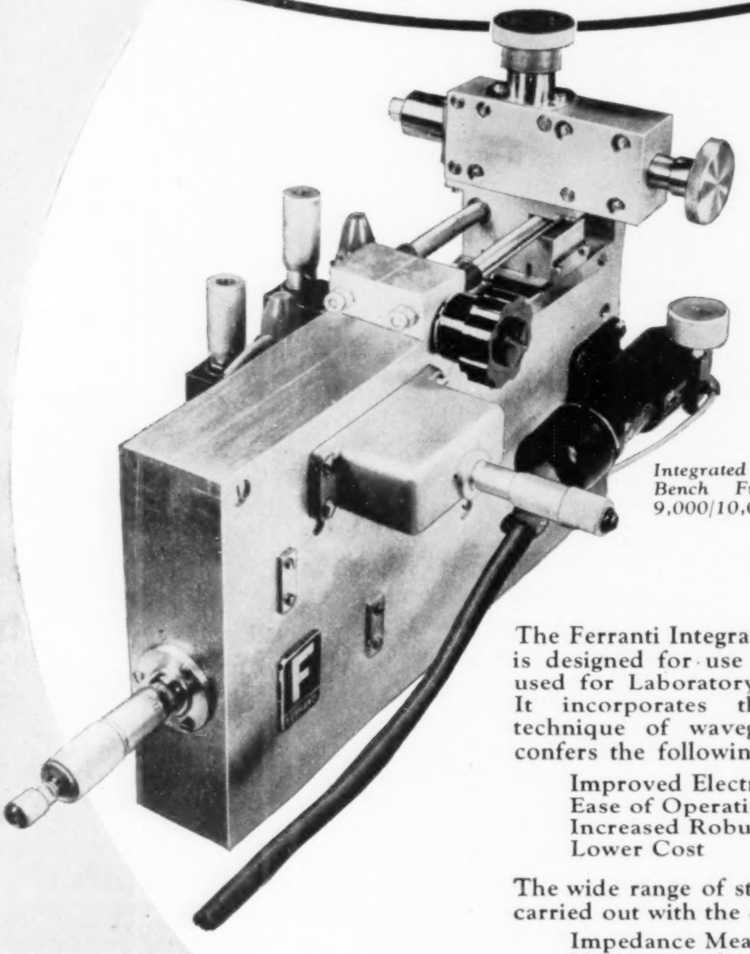
TC 38

The new approach to Microwave Testing



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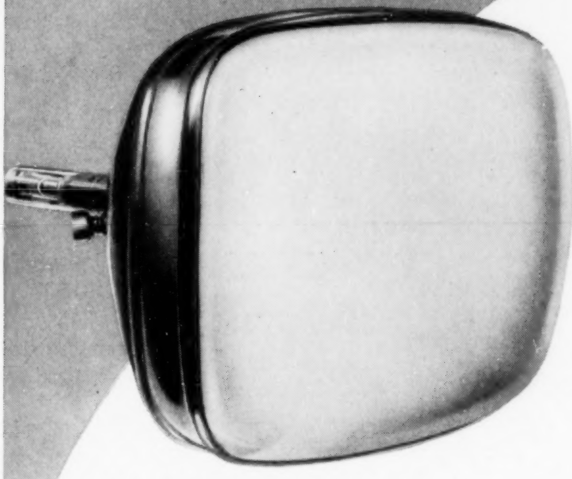
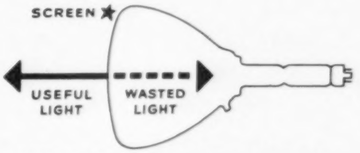


60% brighter pictures
more contrast
extra tube life

An Ediswan Mazda aluminized picture tube gives a picture 60% brighter and more contrasty than is possible with an ordinary tube.

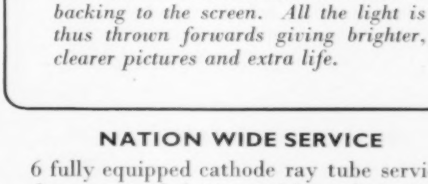
In addition, Ediswan aluminizing protects the screen from ion burn and, with the new Ediswan ion trap tetrode gun to protect the cathode, tube life is increased.

Ediswan production methods, which include the special in-line vacuumizing system, ensure a higher, more uniform standard of lasting efficiency. For complete satisfaction demonstrate and recommend Ediswan Mazda aluminized picture tubes.



WITHOUT ALUMINIZING

Without aluminizing, tubes waste half their light (see diagram above). To counteract this the brilliance must be increased and the tube life is shortened.



WITH EDISWAN ALUMINIZING

Ediswan aluminized tubes have a mirror backing to the screen. All the light is thus thrown forwards giving brighter, clearer pictures and extra life.

RV9

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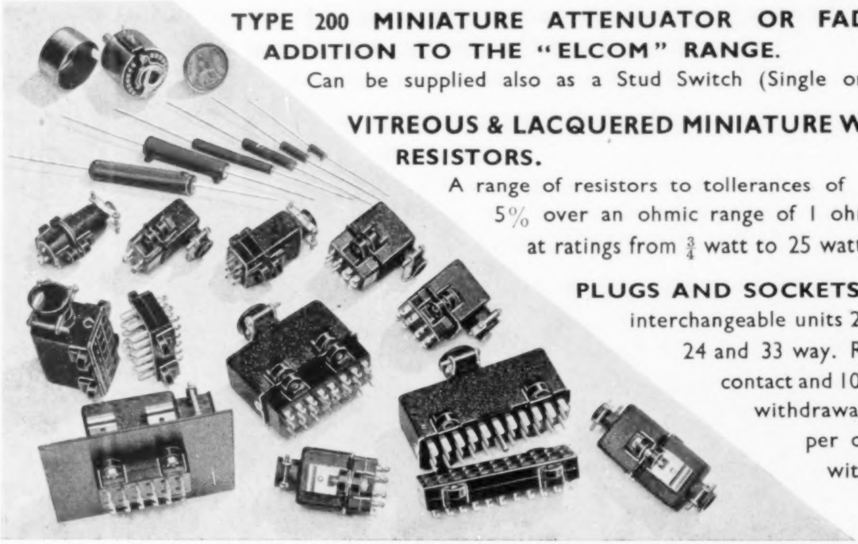

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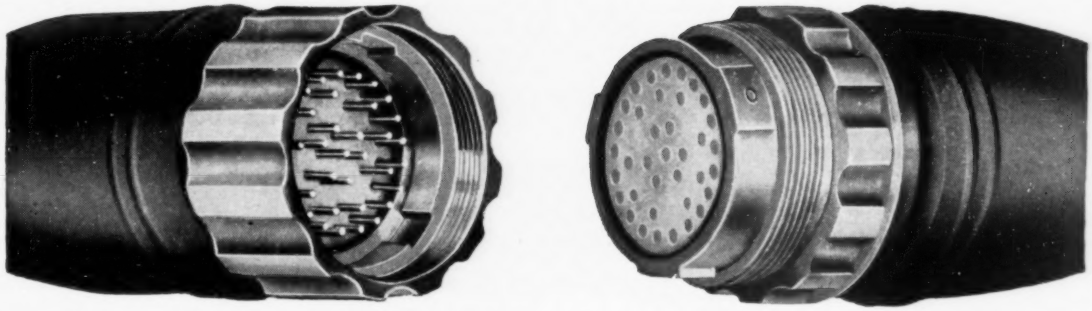

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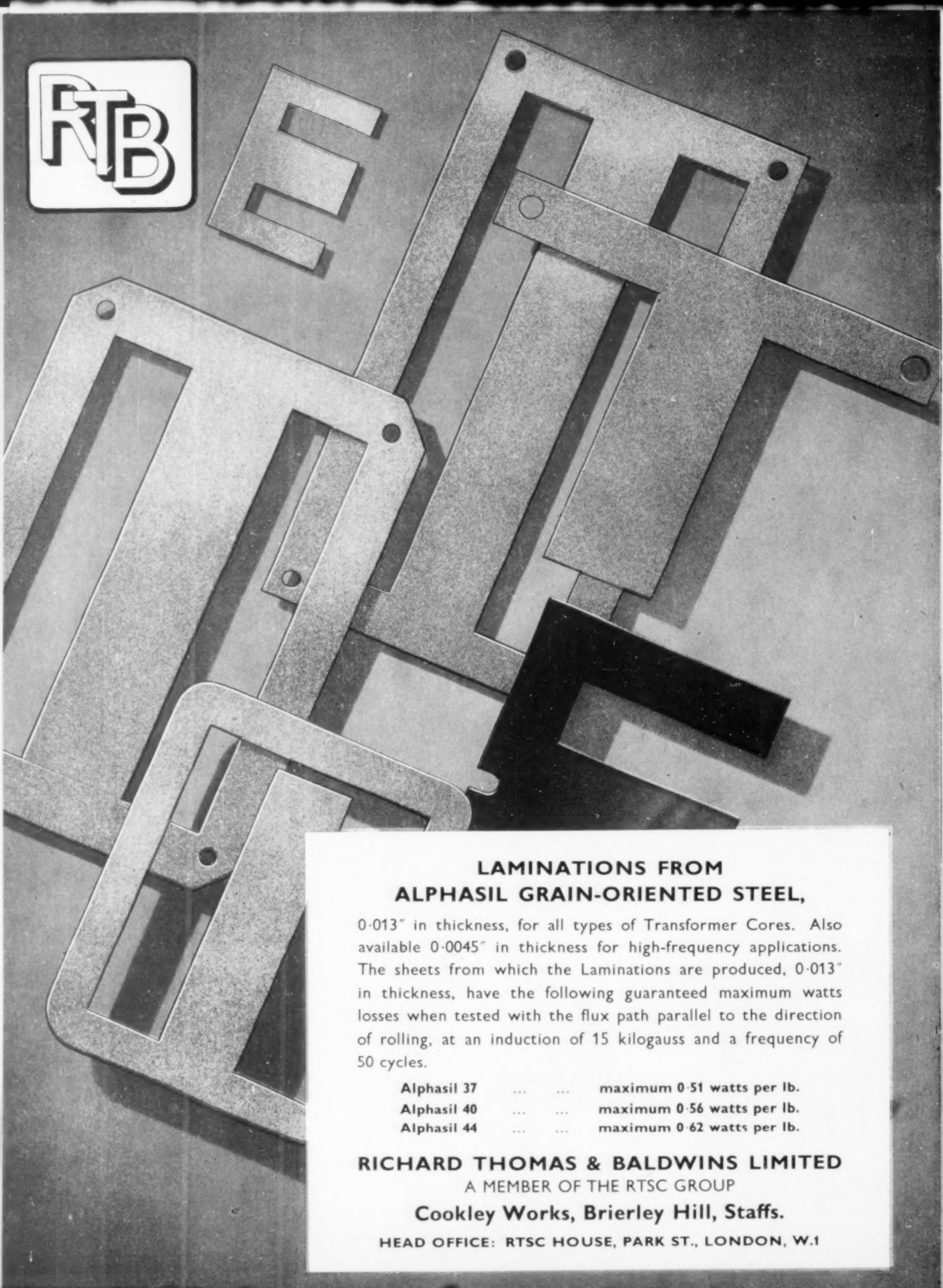

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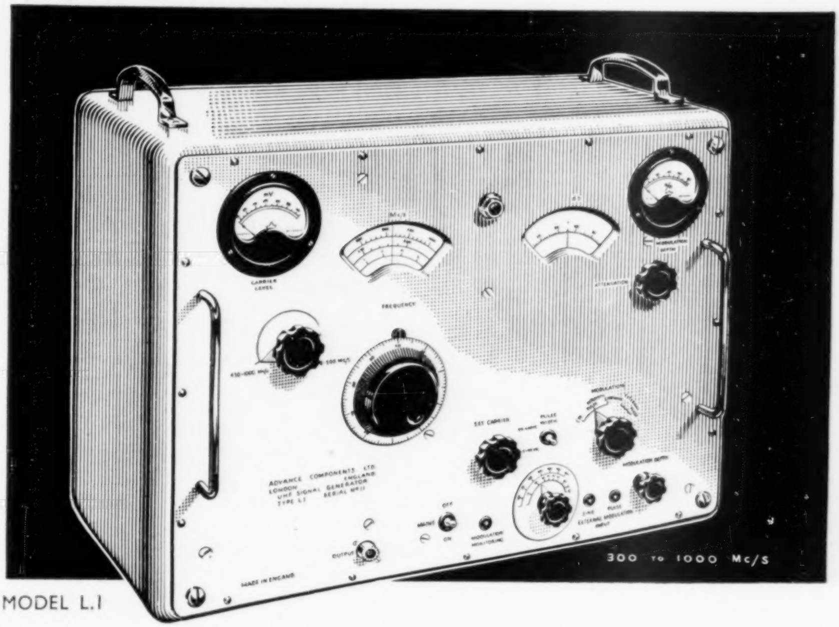

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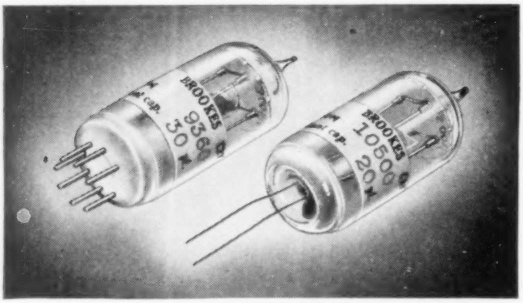

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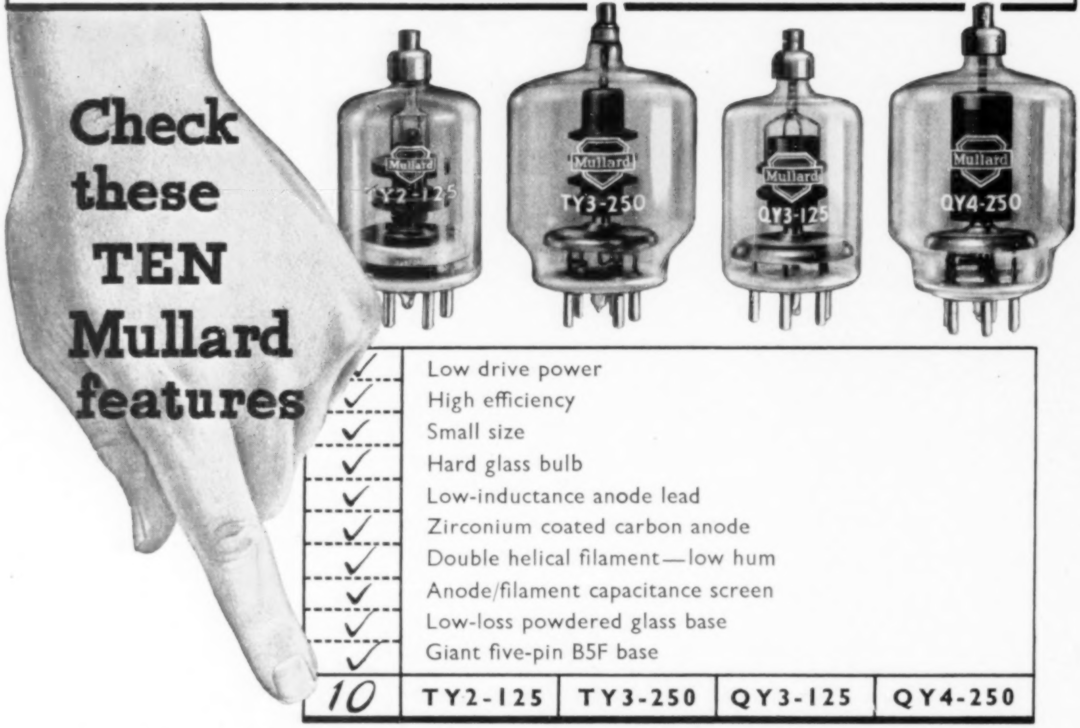

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10	TY2-125	TY3-250	QY3-125	QY4-250

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Detailed information on the above range and other V.H.F. valves made by Mullard may be readily obtained from the address below.

MAXIMUM OPERATING CONDITIONS (CLASS C TELEGRAPHY) at 50 Mc/s									Max. frequency (Mc/s)
Valve	Type of Service	Va (V)	Vgl (V)	Ia (mA)	Igl (mA)	vin(pk) (V)	P load (W)	η (%)	
TY2—125 (CV1924)	ampl.	2500	-200	205	40	390	310	76	200
TY3—250	ampl.	3000	-250	365	69	430	670	77	150
QY3—125 (CV2130)	ampl.	3000	-150	167	6.5	300	300	75	200
QY4—250 (CV2131)	ampl	4000	-225	312	9	374	800	80	120

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Vol. 31 NOVEMBER 1954 No. 11

Faraday Effect in Magnetic Materials

IN June 1952 we discussed the gyrator, a four-pole that violates the reciprocity relation, which had been described by B. D. H. Tellegen in the *Philips Research Reports* of 1948, and in July 1952, under the title of "Microwave Gyrator", we described some experiments that had been made by C. L. Hogan of the Bell Telephone Laboratories on the rotation of the plane of polarization in pieces of ferrite placed in a waveguide. Before Faraday made his discovery it was known that the plane of polarization of light was rotated by crystalline substances, but in 1845 Faraday found that the same thing happened in isotropic substances, especially those with a high refractive index, when subjected to a strong magnetic field in the direction of the beam of light.

Now, after more than a hundred years, interest in the phenomenon has been stirred by the discovery of ferrites, which, while strongly ferromagnetic, are transparent to the centimetric waves commonly employed in waveguides. A drawing of the apparatus employed by Hogan was reproduced in the July 1952 Editorial. As we explained, the applied axial magnetic field aligns the axes of the spinning electrons, and the transverse magnetic field of the beam or wave tends to change the direction of the axes of the spinning electrons and sets up a precessional rotation similar to that of a spinning top, with the result that magnetic fields are produced in all transverse directions. Owing to currents induced in the walls of the waveguide, Gamo* has shown that the rotation is less than in free space and new modes of propagation are excited in the medium, which give rise to beats with the original mode. If the angle of rotation in a given length of ferrite is plotted against the applied axial field, the curve shows humps and depressions instead of a steady increase, unless the length of the specimen is very short.

One can regard the plane-polarized wave as made up of two circularly-polarized waves rotating in opposite directions; the component rotating in the same direction as the Faraday effect, which, in this case, is the direction of the current producing the axial magnetic field, is referred to as the positive component, and the other as the negative component. At a given value of the wave frequency there will be a magnetic field strength at which resonance occurs; this will be when the gyromagnetic precessional rotation and the positive component of the wave have the same angular velocity. Resonance cannot occur with the negative component. Owing to the two components travelling at different velocities and being differently damped, the emerging wave may be elliptically polarized.

In *Philips Research Reports* of April 1954, H. G. Beljers describes some interesting experiments illustrating these points. He also describes tests made with the ceramic permanent magnetic material known as Ferroxdure, the essential component of which is $BaO.\,6Fe_2O_3$. The rotation in the permanently-magnetized material is much less than in magnetically-soft material such as Ferroxcube. The rotation in a length of 2·5 cm was 16·5 degrees with no applied field and this was only reduced to about 14 degrees by applying fields of 2,000 to 3,000 oersteds in either direction, whereas with Ferroxcube these fields would have caused rotations of several hundred degrees; the frequency was 9,400 Mc/s.

An experiment of a different kind described by Beljers involves the application of the Faraday effect to a resonant cavity. In Fig. 1, C is a cylindrical cavity coupled to the waveguide by a hole; the reflecting piston to the right of the cavity is adjusted to match the cavity and guide at the resonant frequency which was about 24,000 Mc/s. The frequency-modulated klystron K provides the microwave energy, and the reflected wave from the cavity is fed through the directional coupler DC to a crystal detector which is connected to the cathode-ray oscilloscope as shown. At the end of the cavity is shown in cross-section a circular slice of Ferroxcube only 0·2 mm thick which can be magnetized by the two poles as shown. On applying the magnetic field, there was first a broadening of the resonance curve and then, as the field strength was increased, a splitting up and separation into two resonance curves as indicated in the figure.

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* *J. Phys. Soc., Japan*, 1953, pp. 176–182.

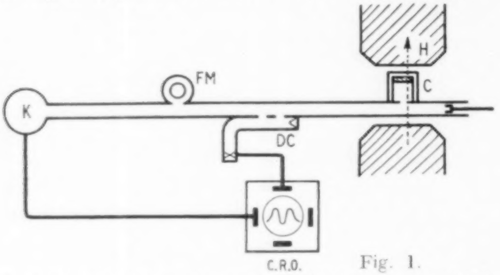

Fig. 1.

This is also shown in Fig. 2 which shows both observed and calculated values. The positive component causes an increase in the resonant frequency, due to increased velocity in the material, and the detuning increases rapidly as gyrostatic resonance is approached, but this is associated with increasing losses, which made measurements near resonance impossible. The negative component causes a small decrease in the resonant frequency of the cavity, and, being free from gyrostatic resonance, settles down to a steady value for very strong magnetic fields.

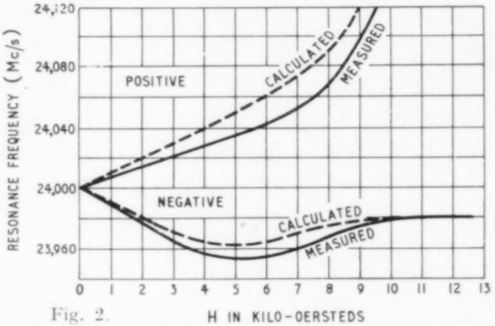

Fig. 2.

It is of interest to note that a four-terminal circuit element which violates the reciprocity law has lately been developed in an entirely different field; viz., by the application of the Hall effect in germanium. This germanium gyrator has been discussed in a recent publication of the Bell Telephone Laboratories (Monograph 2301).

G. W. O. H.

Rotating Observers

IN his letter on p. 306 Professor Cullwick discusses some points in the September Editorial. He suggests that we have never given a convincing proof as to the source of the e.m.f. in the case of the rotating bar magnet with a stationary external circuit. We therefore try again. The galvanometer shows that a current flows in the circuit when the magnet is rotated; the external circuit is at rest in a magnetic field which is undergoing no change whatever either in strength or direction at any point. Surely it follows from this that the source of e.m.f. is in the rotating generator and not in the stationary external circuit. If further proof is required, one can picture the magnet as made up of a large number of separate discs, and if one of these discs were of copper instead of steel, it could be regarded as a Faraday disc rotating in the magnetic field produced by all the other discs. If instead of copper, the disc is of steel, the fact that it contributes its share to the magnetic field does not appreciably affect the induction of the radial e.m.f. in it. In our opinion we have here two convincing proofs, first, that no e.m.f. can be induced in the stationary external circuit, and second, that e.m.f. must be induced in the rotating magnet. It may be possible by means of mathematical jugglery, or by consulting an observer strapped to the rotating magnet, to come to a different conclusion, but we are prepared to leave that to the mathematical juggler or to the dazed observer.

The second point mentioned by Professor Cullwick involves the manner in which the laws of electromagnetism would have to be modified to suit a rotating observer or frame of reference. This led us to conclude that "it is obviously very undesirable to attempt the explanation of electromagnetic or mechanical phenomena from the point of view of a rotating observer".

With regard to the rotation of the earth, we did think of mentioning it, but decided that it was so negligibly small that it could be entirely ignored. If a coil or armature were rotating at 600 r.p.m. the revolutions made in 24 hours would really be 864,000 ± 1, depending on the direction of rotation and the direction of the axis. Is this worth worrying about? G. W. O. H.

ELECTRONIC-RAM EXPERIMENTS

By I. J. Billington, M.Sc.,[*] and W. R. Raudorf, Dr.Phil.[†]

(Physics Department, University of British Columbia)

SUMMARY.—A model of an electronic ram was built and operated to examine experimentally the underlying principle. The work comprised: projecting a 100-mA cylindrical electron beam of 100 cm length; controlling the axial velocity, space-charge density and cross-sectional area of the beam by a steady axially-symmetric magnetic field; the sudden stopping of the beam on entering a region of rapidly increasing magnetic-field intensity to transfer the magnetic energy associated with the whole beam to the electrons at the front of the beam. The results obtained are qualitatively in accordance with theory and indicate the existence of a "ram effect".

Introduction

IN the July 1951 issue of *Wireless Engineer*[‡] a simple method for accelerating electrons to high energies and for generating short and powerful electromagnetic pulses was proposed and discussed. According to this method the magnetic energy which is associated with a cylindrical stream of electrons is used to raise the electrons at the front of the stream to high energy levels.

The apparatus based upon this method represents the electrical analogue of a hydraulic ram, and, for this reason, is called an electronic ram.

A diagram of the basic structure of such an apparatus is given in Fig. 1. It comprises three chambers, placed longitudinally end to end without separating walls, within a sealed evacuated tubular non-magnetic metallic envelope. The length of the second chamber is very great compared to its diameter and many times the length of either the first or the third chamber. The length of the third chamber is greater than its diameter, which is larger than the diameter of the second chamber.

An electron gun in the first chamber serves to project an electron stream of predetermined average velocity axially into and through the second chamber. Solenoidal coils wound around the common tubular envelope serve to produce a static axially-symmetric magnetic field, which is coaxial with respect to the tubular envelope, through the interior of the chambers. The field is uniform and of suitably-chosen intensity within the second chamber, falling off to zero towards the electron gun in the first chamber and rising rapidly at the entrance to the third chamber to a field intensity which is several times larger than that within the second chamber.

The operation of the electronic ram may be summed up as follows.

Under the influence of the steady magnetic field the electrons drawn from the cathode form, as they enter the second chamber, a cylindrical stream which is coaxial with respect to the applied magnetic field. The amount of momentum of an electron at a point of its trajectory is proportional to the difference between the flux traversing the circle through the point considered around the axis of the system, and the flux traversing the circle defined by the point of emission on the cathode. If the applied magnetic field is zero on the cathode, the angular velocity of an electron in chamber 2 is proportional to the uniform flux density there. Hence, the angular velocity is the same for all the electrons passing through chamber 2. The cylindrical structure of the stream is controlled by the steady longitudinal field in the second chamber, and the space-charge density within the beam is uniform and proportional to the square of the flux density. The axial velocity of the electrons in the stream is also uniform and is the same for all the electrons. In other words the electrons obtained from the cathode form a cylindrical beam in chamber 2 which rotates about its axis as a unit and advances much in the same manner as a screw.

Arriving at the junction of the second and third chambers, where the flux density rapidly

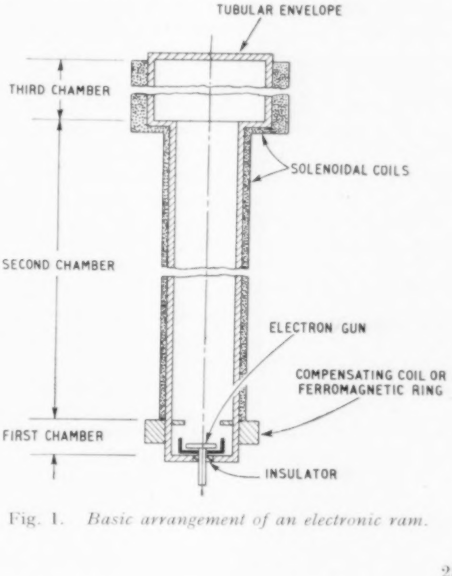

Fig. 1. *Basic arrangement of an electronic ram.*

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[*] Now at The University of Toronto, Canada.
[†] Now at Sir George Williams' College, Montreal, Canada.
[‡] "An Electronic Ram", by W. R. Raudorf.

MS accepted by the Editor, September 1953

increases in the direction of the stream, the strong radial component of the field brings about complete conversion of axial to angular velocity of the electrons constituting the front of the beam. The focusing longitudinal component, on the other hand, causes a compression of that portion of the beam which revolves without advancing, and thereby an increase of the space-charge density. A potential barrier develops which blocks the passage into chamber 3, and against which the succeeding electrons ram. Both space-charge density and potential barrier continue to grow until finally a space-charge limited virtual cathode is formed. At this instant the axial potential gradient becomes negative in chamber 2, positive in chamber 3 and zero at the junction of the two chambers. Once the virtual cathode is set up the entire beam is stopped. The magnetic field which is associated with the beam current collapses during the deceleration process, and induces during its collapse an axial electric field. This induced field is effective in chamber 3 only; in chamber 2 it is compensated by the electric field due to the non-uniform space-charge distribution along the beam caused by the run-on of the electrons. The electric field in chamber 3, generated at the expense of the magnetic energy of the total beam, draws electrons from the virtual cathode and accelerates them through chamber 3.

During the discharge into chamber 3, the space-charge density decreases and the virtual cathode disintegrates as the decelerated beam disperses under the influence of radial inter-electronic forces. Energy considerations show that the energy of the electrons discharged into chamber 3 varies from zero to a maximum value which is given by equation (33).*

From a wave-mechanical point of view the second and third chambers may be considered as waveguides of extremely different impedances [see equation (34)]. This impedance mismatch causes a reflection of the wave train associated with the beam at the junction of the two chambers. In the process of reflection, harmonics of high order are generated in chamber 3, corresponding to the electrons which are accelerated into the terminating tube.

Cylindrical Electron Beam

It is known that a high-density electron beam cannot be projected over large distances under the influence of an electric field alone without appreciable dispersion. Several workers, however, have discussed the possibility of maintaining high density beams of various types in a combined electric and magnetic field (see references 3, 4, 5 of the previous article).

The successful operation of the ram requires a steady cylindrical beam of uniform space-charge density, in which the axial velocity of all the electrons is the same, and in which the space-charge repulsive forces are balanced by magnetic focusing forces, so that the beam may be made as long as desirable without any appreciable change in its cross-section.

The dominant feature of the method for producing such a beam is the projection of a stream of electrons originating from a circular cathode into a steady axial magnetic field. This field is coaxial with respect to the stream and substantially longitudinal for an axial distance in the direction of the stream, the distance being very large relative to the diameter of the stream.

A rigorous analysis of the method is possible under the following conditions:—

1. For an electron beam immersed in a static longitudinal magnetic field to be stable, the forces acting on the electrons in the beam (i.e., Lorentz force, centrifugal force and radial space-charge force) must be in equilibrium. Hence, the second time derivatives of the electron co-ordinates must vanish.
2. Poisson's equation must be satisfied subject to the prescribed boundary conditions fixed by the metallic tubular envelope.
3. The applied magnetic field must be zero at the source of the electrons.

Under these conditions the equations of motion of an electron are readily found and, together with the energy equation, they determine the properties of the beam. It appears that the electrons in the beam individually revolve around the common beam axis with just the required angular velocity to balance the space-charge forces. The angular velocity is proportional to the flux density, and the space-charge density is proportional to the square of the flux density. Therefore, if the beam is immersed in a uniform axial field, the angular velocity is the same for all the electrons, and the space-charge density uniform. The axial velocity in this case is also the same for all the electrons. It is the smaller the greater the flux density of the applied magnetic field. As the flux density increases, the energy of the beam is more and more transformed into rotational energy. If the flux density equals or exceeds the 'critical' or 'limit' value, as defined by equation (19), the axial velocity of the beam is reduced to zero, and the beam cannot advance.

The experimental verification of the theory is subsequently discussed.

Design Considerations

In order to provide a wide range of experimental conditions it was necessary to allow great variability to three important factors: magnetic-field intensity, voltage between cathode and tube, and emission current. Also, the apparatus had to be so constructed that the major components were readily accessible for readjustment or repair.

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* Throughout this article the equation numbers refer to the previous article already cited.

Although all discharge experiments were conducted under high vacuum, any adjustment to the cathode necessitated opening the apparatus and exposing the cathode to the air. Oxide-coated cathodes and thoriated-tungsten cathodes are susceptible to poisoning and easily damaged by ion bombardment. Hence it was decided to employ a directly-heated pure tungsten cathode. Projection of a cylindrical beam, however, of uniform space-charge density requires a plane circular cathode. Its emissive surface should be perpendicular to the axis of the cylindrical tube, and represent an equipotential surface. Moreover, the magnetic field associated with the filament current should be negligibly small.

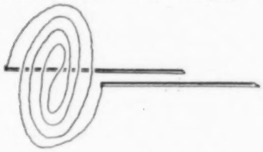

Fig. 2. *Spiral filament with leads.*

The Electron Gun

To approximate an equipotential cathode and avoid an interfering magnetic field the filament was wound in the form of a bifilar spiral (Fig. 2). Tungsten wire of 0·038 cm diameter was chosen to produce a cathode of reasonable rigidity. The ends of the cathode were spot-welded to nickel leads, considerably thicker than the filament wire. A Wehnelt cylinder, of the same diameter as that of the tube forming chamber 2, surrounded the filament spiral. Finally the whole cathode assembly was mounted in a glass ground joint, as shown in Fig. 3. The nickel filament leads were attached to tungsten leads, sealed into glass, with clamps allowing axial adjustment of the cathode position. A centre-tapped transformer supplied the filament power which was controlled by a Variac on the primary side.

Vacuum System and Power Supply

For evacuating the system a mechanical forepump and a mercury-vapour diffusion pump were used. Pressures were measured with a Pirani gauge. The experiments were carried out at pressures below 10^{-5} cm Hg.

For certain experiments a d.c. power supply was used, in which case the positive terminal was connected to the earthed tube and the negative terminal to the cathode via the centre tap of the filament transformer. For pulsed operation the secondary of a 3-kVA transformer was connected between tube and cathode. A Variac on the primary of the h.t. transformer permitted variation of the accelerating voltage. For a given position of the cathode and temperature of the filament, the applied voltage was chosen so that saturation current was drawn for the greater part of each half-cycle during which the cathode was negative. Furthermore, the magnetic field was adjusted so that the beam could not enter the tube during the half-cycle before saturation voltage was attained [Equ. (21)]. Under such conditions the current pulses passing down the tube should be almost square-wave pulses.

Short Experimental Tube

Preliminary investigations of the formation of electron beams were carried out, using a brass tube of 18 cm length and 1·33 cm inner diameter. A coil around the tube along its whole length served to provide a uniform axial magnetic field inside the tube. To compensate the focusing magnetic field at the cathode, a short compensating coil, about 1 cm long, was added at the cathode end. Fluxmeter measurements showed that the cathode region could be made field-free in this way. The cathode end of the tube was connected to a short brass cylinder (Fig. 3), large enough to fit over a length of glass tubing attached to the ground joint for the electron gun. The glass-to-metal vacuum seal consisted of a threaded ring which screwed on the brass cylinder and held an O-ring rubber seal in place between the brass and the glass tubing.

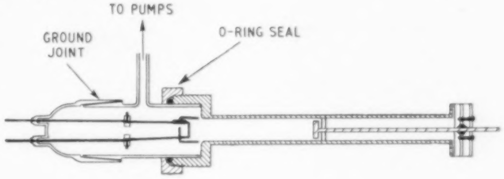

Fig. 3. *18-cm experimental tube; travelling probe and cathode assembly shown in position.*

In order to study the variation of field current with axial distance from the cathode, a travelling collector was designed. A metal disc (Fig. 3) with diameter slightly smaller than that of the tube was attached to the end of a brass rod inserted in the tube. Behind the disc was a dielectric spacer of slightly larger diameter, to prevent the disc from making contact with the tube. At the end of the tube the brass rod passed through a vacuum seal consisting of two discs clamped together and pressing a rubber O-ring against the rod. This seal allowed the probe to be moved backwards and forwards inside the tube while the system was evacuated. An ammeter, inserted between probe and ground, measured the beam current as dependent on position by sliding the probe along the tube.

The Ram Model

The main tube forming the second chamber of the ram model had an inner diameter of 1·33 cm and a length of 100 cm. The tube constituting the third chamber was 7·2 cm in diameter and 15 cm in length. The end of this tube was closed except for a hole 1·6 cm in diameter (Fig. 4). The cathode-end termination of the main tube was identical with that described above for the short tube and illustrated in Fig. 3.

A first coil of four layers of enamelled copper wire of 0·51 mm diameter was wound along the whole length of the tube. A second coil of the same wire was wound on top of the first. Two layers of this coil started 2·5 cm from the cathode and also extended to the end of the tube. The first and second coils, connected to variable resistors to control the current, could be connected either in series, if a small current through both coils was required, or in parallel to obtain a larger current in each coil. With the two coils arranged as described a uniform field could be obtained over most of the length of the main tube except for the first few centimetres where a region of increasing field existed. At the end of the long tube a 'bunching coil' of about 500 turns was wound against the end of the terminating tube, as shown in Fig. 4. This coil was designed to produce a magnetic field, of intensity greater than that of the limiting field, at the junction of the two tubes.

Finally, in order to provide a strong magnetic field in the terminating tube, a coil of eight layers of the same wire as for the other coils was wound on the outside of this tube. The electron gun used was the same as for the short-tube experiments.

The probe previously described could be pushed through the terminating tube into the main tube to investigate the beam current (Fig. 5). To investigate the current in the terminating tube, two methods were employed. A hollow cylindrical collector could be placed over the hole in the terminating tube (Fig. 6), or a similarly-shaped collector on the end of the rod could be placed inside the tube, as shown in Fig. 4. These collectors were made hollow in an attempt to prevent secondary emission when high-energy electrons hit the collector. It appeared,

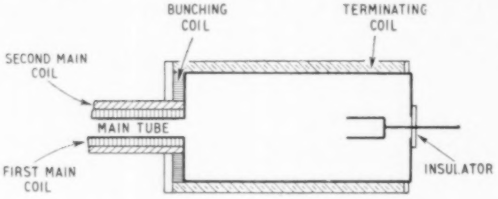

Fig. 4. *Terminating tube, showing coil positions and internal collector.*

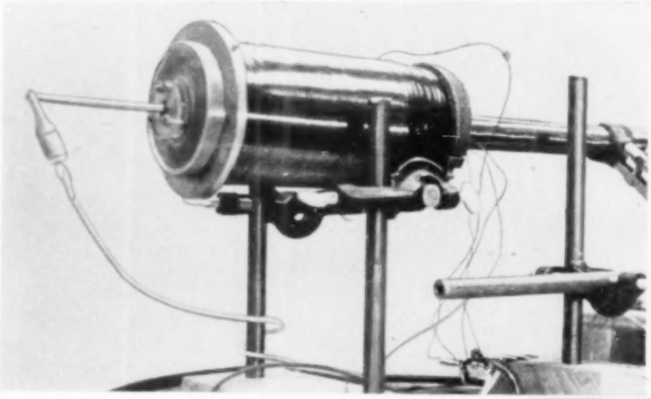

Fig. 5. *Terminating tube with travelling probe in position.*

TABLE 1

SPECIFICATION OF THE RAM MODEL

	Diameter (cm)	Length (cm)
Tungsten filament wire	0·038	10
Filament spiral	0·9	—
Wehnelt cylinder	1·3	1
Main tube	1·33	100
Terminating tube	7·2	15
Travelling probe	1·1	—
Cylindrical collector	1·3	3
Axial distance between cathode and main tube	0·5 cm	
Wehnelt cylinder and main tube	0·25 cm	

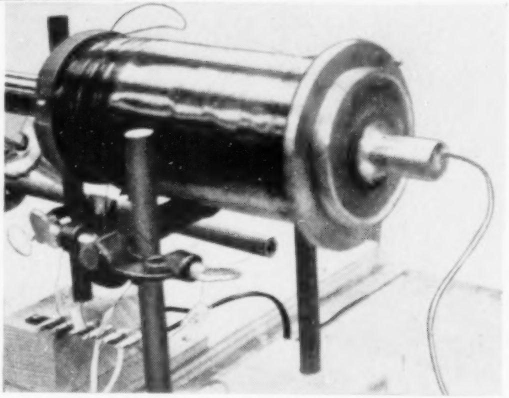

Fig. 6. *Terminating tube with external collector.*

however, that secondary emission was not well suppressed in spite of these precautions. The design specification of the ram model is given in Table 1.

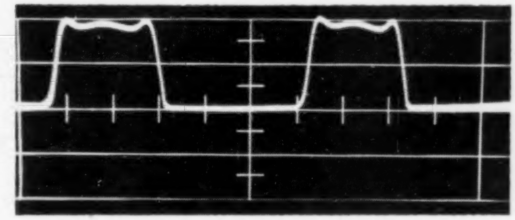

Fig. 7. *Unperturbed square wave in main tube as displayed on screen of Tektronix Oscilloscope, model 514-D.*

Experimental Results

Examination of the heated cathode with an optical pyrometer showed that there was an appreciable cooling effect in the outer turn of the spiral due to heat conduction by the cathode leads. Therefore, the total emission current which could be drawn was considerably less than the calculated value. It was found that total emission currents of about 100 mA required a filament power of approximately 100 W.

Operating the tube 18 cm long (Fig. 3) d.c. measurements were taken with the travelling probe to determine the variation of beam current with distance along the tube. A series of measurements with the probe at positions between 5 cm and 18 cm from the cathode end of the tube showed no appreciable variation of beam current with distance. Beam currents as high as 65% of the total emission current and as large as 100 mA were detected. Passage of larger currents was limited only by the capacity of the d.c. power supply used. However, when the probe was at the entrance to the main tube, effectively changing the electron optics, approximately 80% of the total emission current was registered on the probe.

Pulse measurements, using the pulsing system previously described, were taken to determine the pulsed beam current passing down the tube. The waveform of the pulses arriving at the end of the tube was examined on a c.r. tube and was similar to that shown in Fig. 7. Some irregularities of the waveform were probably due to variation of the electron optics with the sinusoidal voltage between cathode and tube.

Similar experiments were carried out with the ram model. The beam-detecting probe was placed at the end of the 100-cm tube, the current in the field coils and the voltage applied to the cathode were adjusted to give the same conditions under which the short tube d.c. experiments were performed. The current distribution turned out to be the same as that in the 18-cm tube. Again about 65% were collected at the end of the 100-cm tube when the total emission was 150 mA.

With 60-c/s a.c. operation the probe current pulses were examined with a c.r. tube which actually recorded the voltage across a 10-ohm resistor in the output circuit. Fig. 8 shows a photograph of the waveform as displayed on the oscilloscope screen.

Measurements with a d.c. ammeter were then taken of the pulse beam current received by the cylindrical collector (Fig. 6) at the end of chamber 3. With the focusing magnetic field only in chamber 2 no average beam current was registered, obviously because of dispersion of the beam in chamber 3 due to unbalanced centrifugal and space-charge forces. However, with current flowing in the terminating coil also, a small beam current, about 5% of the total emission, was detected. Similar results were obtained using a collector within chamber 3 (Fig. 4). Operating the bunching coil as well produced a slight decrease in the beam current.

Examination of the collector current with the c.r. tube gave evidence of a 'ram effect'. Fig. 7 shows the unperturbed square wave as received with the travelling probe just inside the main tube. The flux density in the main tube was about 270 gauss, and the voltage between cathode and tube 600 V r.m.s.

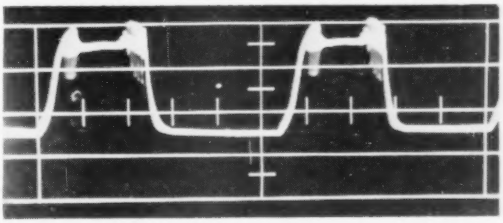

Fig. 8. *Perturbed square wave in terminating tube showing small oscillations at the edges of the square wave as critical conditions are approached.*

Fig. 8 shows a perturbed square wave obtained with the external collector on the terminating tube, applying a flux density of about 270 gauss in the main tube, and at least 300 gauss in the terminating tube, and 800 V r.m.s. to the cathode. Increasing the voltage between cathode and tube, or decreasing the flux density in chamber 3, made the small oscillations at both ends of each square wave disappear. Since a sinusoidal voltage was applied to the cathode, equation (17) predicts that a bunching effect should be first noticeable towards the edges of the square wave where the voltage is low enough to cause critical conditions.

Keeping the flux densities unchanged, but reducing the cathode voltage to 600 V r.m.s., caused the oscillations to spread across the whole square wave, the duration of which was less than 1/120 sec (Fig. 9). In all cases the maximum beam current through chamber 2 was about 80 mA.

Calculations in which the diameter of the electron beam was assumed to be 1 cm, showed that the bunching effect occurred under conditions close to those predicted by the theory.

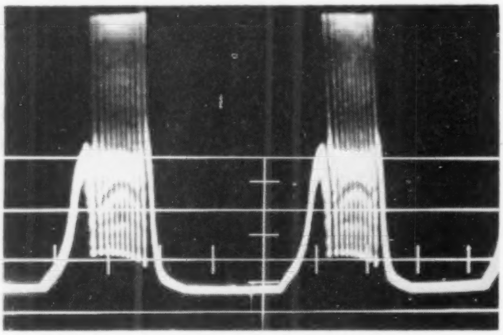

Fig. 9. *Perturbed square wave in terminating tube under critical conditions.*

Discussion

The peak current of the oscillations depicted in Fig. 9 considerably exceeds the value of the current traversing chamber 3 under steady conditions, and this fact suggests that the electrons which constitute these peaks possess higher axial velocity on the average than the electrons within chamber 2. It appears that each square wave was of sufficient duration for the electron beam to undergo the bunching several times in each cycle. Apparently the bunching magnetic field acts like a valve which closes when the current density surpasses the critical value and opens when it drops below this value. Referring to Fig. 9, which shows the collector current versus time, the oscillations superimposed on the square wave may be explained as follows: the first peak on the left just above the top line of reference represents the critical current; i.e., maximum current which can be passed according to Equ. (21). The current cannot exceed this value; on the contrary, it falls off as the potential barrier develops due to the bunching of the electron beam as it enters the strong magnetic field in chamber 3. It can be seen from the trace on the oscillogram that the current does not fall off to zero, indicating that the axial velocity of the electrons was never completely reduced to zero. It is probable that the conditions assumed for the derivation of Equ. (17) were only approximated with the simple electron gun used in the experimental apparatus. Once a virtual cathode has formed, the conditions become unstable and a sharp pulse is ejected almost instantaneously into the terminating tube, indicated by the second peak high above the top line of reference. During this discharge the virtual cathode and the beam in chamber 2 disintegrate. A new beam is formed, the collector current begins to flow, rises to its critical value (see thicker portion of the trace between first two top lines of reference), falls off for reasons already given, and the whole process is repeated.

Efforts were made to determine the energy of the electrons received by the collector. A 5-kV electrostatic voltmeter was placed between the collector and ground, but registered nothing. In another experiment a peak voltage of 200 V was applied to the cathode, the magnetic field being adjusted to produce the bunching effect, and the collector was maintained at a negative potential of 1,000 V relative to the grounded tube. The c.r. tube indicated that some collector current may have been received, since small current pips were observed on the screen. However, it seems that the results of both experiments were decisively modified by secondary emission from the surface of the collector.

Conclusion

The main purpose of this simple ram model was to investigate qualitatively the basic principle underlying the proposed discharge device. For a quantitative study of the whole discharge process, however, an essentially improved model would be necessary to permit accurate determination of the energy of the output electrons.

Acknowledgment

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MULTILOOP FEEDBACK AMPLIFIERS

A Stability Criterion

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Introduction

BODE[1] has given a stability criterion for multiloop feedback amplifiers involving, in general, a large number of plots of Nyquist type. In this paper a stability criterion for multiloop feedback amplifiers is derived which involves only one Nyquist plot.

1. Gain Functions for some Multiloop Feedback Amplifiers

Fig. 1 shows three possibilities for a two-stage multiloop feedback amplifier. The external gains of these amplifiers can be calculated by a similar process to that used for calculating the gain of a single-loop amplifier. Thus, for the amplifier (a) in Fig. 1, if E_s is the externally applied signal voltage, E the output voltage and E_1 the output voltage from amplifier A_1 we have,

$$\left.\begin{aligned}(E_s + \beta_2 E)\, A_1 &= E_1\\ (E_1 + \beta_1 E)\, A_2 &= E\end{aligned}\right\}$$

and eliminating E_1 from the above equations the external gain, G say, is found to be given by,

$$G = \frac{E}{E_s} = \frac{A_1 A_2}{1 - A_1 A_2 \beta_2 - A_2 \beta_1} \quad .. \quad (1a)$$

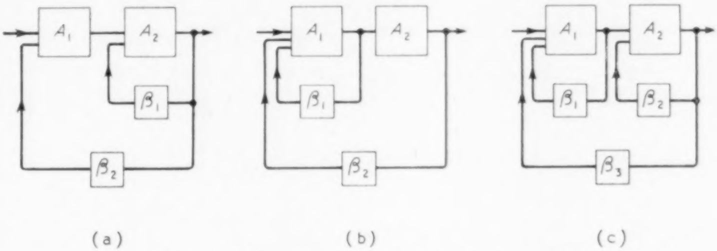

Fig. 1. *Possible two-stage multiloop feedback amplifiers.*

Similarly the amplifiers (b) and (c) in Fig. 1 will have external gains given, respectively, by,

$$G = \frac{A_1 A_2}{1 - A_1 A_2 \beta_2 - A_1 \beta_1} \quad .. \quad .. \quad (1b)$$

and

$$G = \frac{A_1 A_2}{1 - A_1 \beta_1 - A_1 A_2 \beta_3 - A_2 \beta_2 + A_1 A_2 \beta_1 \beta_2} \quad .. \quad .. \quad .. \quad (1c)$$

2. Stability Criteria for the above Multiloop Amplifiers

Using the same argument as in Sections 1 and 2 of the companion paper on single-loop amplifiers* it is seen that the multiloop amplifiers of Fig. 1 will be stable when connected up provided the appropriate G has no poles in the right-half p-plane. Since A_1 and A_2 themselves are supposed to be free from feedback loops, $A_1 A_2$ can have no poles in the right-half p-plane and hence G has poles in the right-half p-plane if the denominator of the appropriate expression (1a) to (1c) has zeros in the right-half p-plane, otherwise not.

Thus, the necessary and sufficient conditions for the stability of one of the amplifiers (a) to (c) is that the denominator of the expression on the right-hand side of the appropriate equations (1a) to (1c) should be a minimum-phase function.

In Nyquist form, amplifier (c) for example, will be stable provided the plot of

$$(1 - A_1\beta_1 - A_1A_2\beta_3 - A_2\beta_2 + A_1A_2\beta_1\beta_2),$$

or

$$(-A_1\beta_1 - A_1A_2\beta_3 - A_2\beta_2 + A_1A_2\beta_1\beta_2),$$

or

$$(A_1\beta_1 + A_1A_2\beta_3 + A_2\beta_2 - A_1A_2\beta_1\beta_2)$$

and its complex conjugate for all frequencies from 0 to $+\infty$ does not enclose the points (0,0), $(-1{,}0)$ or (1,0) respectively, otherwise not. Similarly for amplifiers (a) and (b).

3. General Criterion for Multiloop Amplifiers

The general expression for the external gain of a multiloop feedback amplifier (supposing that it is possible to decompose the amplifier into separate A and β sections) can be written as the ratio of two quantities each of which will involve the algebraic sum of terms consisting of products of various A and β terms. Since the individual A and β terms can have no poles in the right-half p-plane the numerator quantity can have no poles in the right-half p-plane; and so the stability or otherwise of the system is determined by

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* *Wireless Engineer*, p. 274, October 1954.

whether or not the denominator quantity has any zeros in the right-half p-plane. As the denominator can have no poles in the right-half p-plane, the system will be stable if the denominator quantity is a minimum-phase function, otherwise not. This might be determined by a Nyquist plot of the denominator quantity, or (1 − denominator), as with single-loop amplifiers.

As with single-loop amplifiers, it is possible for a multiloop amplifier to be stable when all valves have their normal gain but to become unstable when the gain of one or more valves is reduced in value. The situation is complicated in the case of multiloop amplifiers by the fact that a reduction in gain of a valve can, in general, either increase or decrease the Nyquist vector for a given frequency and would also, in general, change the shape of the Nyquist plot. If of interest, this question of the possibility of gain reduction of the valves causing instability would require further consideration.

REFERENCE

[1] H. W. Bode, "Network Analysis and Feedback Amplifier Design". (D. Van Nostrand 1945), pp. 157-162.

SOLUTION OF CUBICS AND QUARTICS

By A. C. Sim

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SUMMARY.—A routine for the determination of the roots of cubic equations is developed specifically to meet the requirements of circuit designers. The method is based upon that used by Emde and is organized so that the solutions are developed with minimum effort. Three significant figures can be obtained using a slide-rule for the subsidiary computations.

Ferrari's method for reducing a quartic equation is utilized to develop a similar routine to determine the quadratic factors.

Simple checks are provided at appropriate stages in the routines, and a few numerical examples are included. A collection of cubic and quartic Laplace Transforms is appended.

1. Introduction

It can be rightly claimed that engineers have special requirements in computational problems, and there is yet a need to meet these requirements in the case of the solution of polynomial equations. The present note is aimed at doing this for cubic and quartic equations.

In ordinary circuit design it is seldom economical to solve high-degree equations which may arise, and the need to determine the roots of cubic or quartic equations is, in general, only occasionally encountered except in special fields. It is important that the method of solution to be adopted should not strain the memory, and should take advantage of the general lack of precision that can be tolerated (three significant figures normally sufficing). The first requirement is to be met by offering a single routine which succeeds in all cases, and advantage of the second is taken by presenting part of the solution graphically and by simplifying the formulae.

The basis of the method consists in reducing the cubic equation to a form which contains only one arbitrary parameter. Such a procedure has been used by Emde,[1] and Katz,[2] but does not appear to have received the popularity it deserves. The above authors have presented the roots of the reduced equation in tabular form, the roots of the original equation being obtainable from them. This procedure is not always satisfactory because of the differences between like quantities arising in the formulae. The method will here be reorganized to avoid such difficulties, and to ensure that adequate accuracy is always obtained.

2. Cubic Equations

Let the equation be written

$$(p^3 + a_2p^2 + a_1p + a_0) = 0 \quad \text{..} \quad \text{..} \quad (1)$$

To obtain the reduced form of this equation, which will serve as a basis for the method, introduce a variable x defined by:

$$x = (p + \tfrac{1}{3}a_2)/K' \quad \text{..} \quad \text{..} \quad \text{..} \quad (2)$$

where K' is a constant to be selected. Substitution into Equ. (1) gives an equation for x:

$$\{K'^3x^3 + (a_1 - \tfrac{1}{3}a_2^2)\,K'x + (\tfrac{2}{27}\,a_2^3 - \tfrac{1}{3}a_1a_2 + a_0)\} = 0 \quad \text{..} \quad \text{..} \quad (3)$$

If K' is now chosen to be a real root of

$$K'^3 = (\tfrac{1}{27}\,a_2^3 - \tfrac{1}{6}\,a_1a_2 + \tfrac{1}{2}\,a_0) \quad \text{..} \quad (4)$$

then the equation can be put in the form:[*]—

$$(x^3 + 2) = \lambda x \quad \text{..} \quad \text{..} \quad \text{..} \quad (5)$$

$$\text{where } \lambda = (\tfrac{1}{3}a_2^2 - a_1)/K'^2 \quad \text{..} \quad \text{..} \quad \text{..} \quad (6)$$

Suppose that a real root α is obtained from Equ. (5). Then it follows that the remaining two roots must be solutions of the quadratic:

$$(x^2 + \alpha x - 2/\alpha) = 0 \quad \text{..} \quad \text{..} \quad (7)$$

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[This can be seen by multiplying the quadratic by $(x - \alpha)$.] The remaining roots β and γ are thus

$$\beta = -\frac{\alpha}{2}[1 + (1 + 8/\alpha^3)^{\frac{1}{2}}]$$

$$\gamma = -\frac{\alpha}{2}[1 - (1 + 8/\alpha^3)^{\frac{1}{2}}] \quad .. \quad .. \quad (8)$$

and the three roots must satisfy the well-known[3] relationships:—

$$\alpha\beta\gamma = -2$$

$$(\alpha + \beta + \gamma) = 0$$

$$\left(\frac{1}{\alpha} + \frac{1}{\beta} + \frac{1}{\gamma}\right) = \frac{\lambda}{2} \quad .. \quad .. \quad .. \quad (9)$$

These allow Equ. (8) to be written in a form which avoids the calculation of α^3 and the difference between two like quantities in γ:

$$\beta = -\tfrac{1}{2}[\alpha + (\lambda + 6/\alpha)^{\frac{1}{2}}]$$

$$\gamma = -2/\alpha\beta \quad .. \quad .. \quad .. \quad .. \quad (10)$$

3. Series Expansions

Convenient expansions which converge rapidly in the neighbourhood of any given value of λ can be obtained from the reversion[4] of Equ. (5). When λ is numerically large there results:—

$$\alpha \approx \frac{2}{\lambda}\left\{1 - \frac{4}{\lambda^3} + \frac{48}{\lambda^6} - \text{-----}\right\}(|\lambda| \gg 1) \quad (11)$$

Equs. (8) then give correspondingly:

$$\beta, \gamma \approx \left\{-\frac{\alpha}{2} \pm \sqrt{\lambda}\left[1 + \frac{3}{2\lambda^3} - \frac{105}{8\lambda^6} + \text{--}\right]\right\}$$

$$(|\lambda| \gg 1) \quad .. \quad .. \quad .. \quad (12)$$

The direct reversion of Equ. (5) gives a series appropriate for small λ, but this is not required. Further expansion is necessary around the value $\lambda = 3$ since this is the point at which two complex roots appear ($\lambda < 3$). It is readily found that if

$$\delta = (\lambda - 3)/9 \quad .. \quad .. \quad .. \quad .. \quad (13)$$

then

$$\alpha \approx -2\{1 + \delta - \delta^2/3 + \delta^3/9 - \delta^4/9 + \text{---}\}$$

$$.. \quad .. \quad .. \quad .. \quad (14)$$

$$\beta, \gamma \approx \{-\alpha/2 \pm \sqrt{3\delta}[1 - \delta/6 + 5\delta^2/24 - \delta^3/48 \text{---}]\}$$

$$.. \quad .. \quad .. \quad .. \quad (15)$$

When $|\lambda|$ is large it is convenient to compute the roots of the original equations directly. Introduce the following constants:

$$K_1 = (9a_1a_2 - 2a_2^3 - 27a_0)$$

$$K_2 = (a_2^2 - 3a_1)$$

$$K_3 = K_1^2/108K_2^3 \; (= 1/\lambda^3) \quad .. \quad .. \quad (16)$$

Then $K' = \frac{1}{3}(\frac{1}{2}K_1)^{\frac{1}{3}}$ and $\lambda = K_2/3K'^2$. The expansions (11) and (12) then give direct formulae for the roots of the original equation:

$$p_1 = -\left\{\tfrac{1}{3}a_2 + \frac{K_1}{9K_2}[1 + 4K_3 + 48K_3^2 + \text{--}]\right\}$$

$$.. \quad .. \quad .. \quad .. \quad (17)$$

$$p_2, p_3 = -\left\{\tfrac{1}{2}p_1 + \tfrac{1}{2}a_2 + \right.$$

$$\left. \pm \frac{1}{\sqrt{3K_2}}\left[1 - \frac{3}{2}K_3 + \frac{105}{8}K_3^2 \ldots\right]\right\} \quad .. \quad (18)$$

provided K_3 is small enough.

If an approximate solution, α, to Equ. (5) is known and greater accuracy is required, then Taylor's theorem gives for an improved solution, α',

$$\alpha' = \alpha + \frac{(\alpha^3 + 2 - \lambda\alpha)}{(3\alpha^2 - \lambda)} \quad .. \quad .. \quad (19)$$

and iteration of this equation will rapidly produce any desired number of significant figures.

One final expansion is perhaps worth including. If a root α_0 is known corresponding to a coefficient λ_0, and the root α corresponding to $\lambda \approx \lambda_0$ is required, then:—

$$\alpha \approx \left\{\alpha_0 + \frac{(\lambda - \lambda_0)\alpha_0}{(3\alpha_0^2 - \lambda)} - \frac{3(\lambda - \lambda_0)^2\alpha_0^3}{(3\alpha_0^2 - \lambda)^3}\right.$$

$$\left. + \frac{(15\alpha_0^2 + \lambda)(\lambda - \lambda_0)^3\alpha_0^3}{(3\alpha_0^2 - \lambda)^5} \ldots\right\} \quad (20)$$

This expansion may be of value in assessing the effect of component tolerances upon circuit performance.

4. Quartics

The coefficients of the quartic are defined as follows:

$$[p^4 + a_3p^3 + a_2p^2 + a_1p + a_0] = 0 \quad .. \quad (21)$$

Ferrari's[3] method of reducing this equation is to assume that it can be expressed in the form

$$(p^2 + \tfrac{1}{2}a_3p + \tfrac{1}{6}a_2 + \tfrac{1}{3}z)^2 = (\tfrac{1}{2}Mp + \tfrac{1}{6}N)^2 \quad (22)$$

where z, M, and N, have to be selected so that (22) and (21) agree. A comparison of these two forms of equation leads to three subsidiary equations:

$$M^2 = \left(a_3^2 - \tfrac{8}{3}a_2 + \tfrac{8}{3}z\right)$$

$$N^2 = [(a_2 + 2z)^2 - 36a_0]$$

$$MN = (a_2a_3 - 6a_1 + 2a_3z) \quad .. \quad .. \quad (23)$$

and by eliminating M and N it is seen that z must be a solution of the cubic equation:

$$(z^3 + \tfrac{1}{32}J^3) = \tfrac{3}{4}Iz \quad .. \quad .. \quad .. \quad (24)$$

in which $I = (12a_0 - 3a_1a_3 + a_2^2)$

$$\text{and} \quad J^3 = \begin{vmatrix} 12a_0 & 3a_1 & 2a_2 \\ 3a_1 & 2a_2 & 3a_3 \\ 2a_2 & 3a_3 & 12 \end{vmatrix} \quad .. \quad .. \quad (25)$$

If $\lambda = 12I/J^2$, then $z = J\alpha/4$, where α is any root of Equ. (5) for this value of λ. When $|\lambda| \leqslant 10$, α is shown in Figs. 1 or 2, and for $|\lambda| > 10$, Equ. (11) is convenient so that $\alpha \to 0$ as $\lambda \to \pm\infty$. Once a value has been assigned to z, M and N can be found from Equ. (23). If Equ. (22) is then factorized the quartic will be reduced to two quadratic factors and the roots readily found.

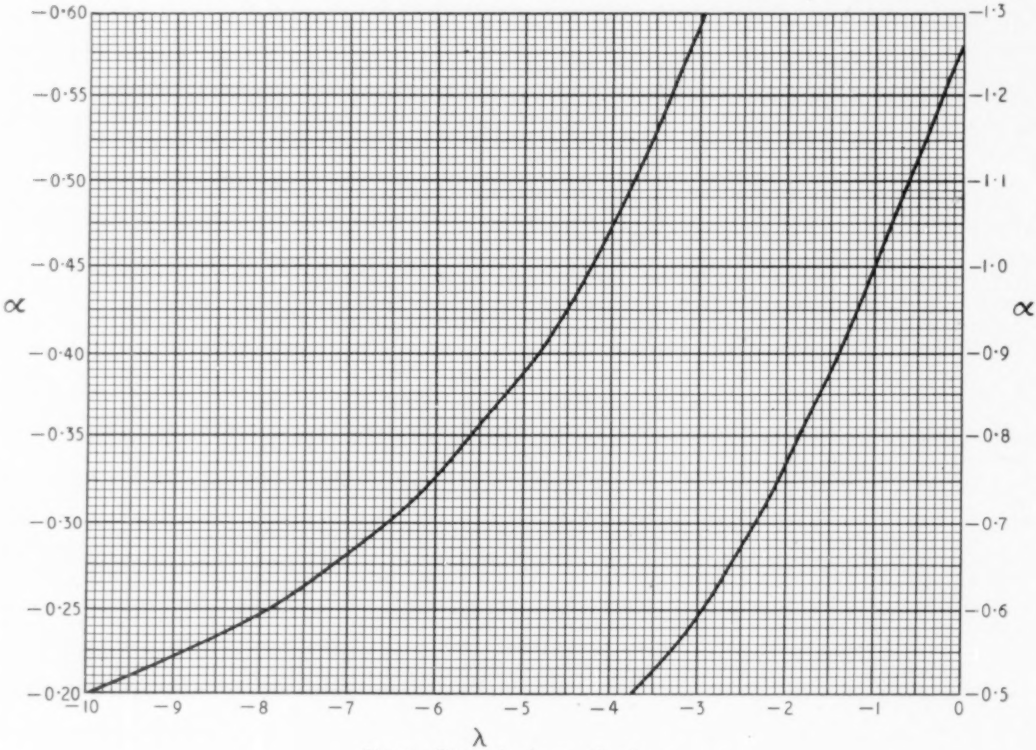

Fig. 1. *The root α for negative λ.*

5. Root Calculations

In special critical cases there may be difficulties in obtaining sufficient precision; for example when the real and imaginary parts of a complex root differ largely in magnitude, the difficulty arises in the determination of the smaller quantity.

In the cubic routine all such difficulties have been eliminated by careful choice of procedure, and by determining three basic numbers involved very accurately. These involve only simple products of the coefficients and high accuracy is possible without undue effort (say five significant figures). If a large cancellation of terms is encountered in computing these quantities, then due consideration must be given to the accuracy with which the original coefficients are known since a small change in any one of them might then result in a large change in the roots.

The computation is greatly facilitated if Barlow's[5] tables of squares, cubes, cube roots, etc., are at hand.

Cubic Routine:—

Write the equation in the form:—

$$[p^3 + a_2p^2 + a_1p + a_0] = 0$$

and then proceed as follows:—

(i) Calculate accurately

$$K_1 = (9a_1a_2 - 2a_2^3 - 27a_0)$$
$$K_2 = (a_2^2 - 3a_1)$$

(ii) Calculate by slide-rule

$$K_3 = K_1^2/108K_2^3$$

(a) If $|K_3| \leqslant 0{\cdot}001$ the three roots are:

$$p_1 \approx -[\tfrac{1}{3}a_2 + K_1/9K_2]$$
$$p_2, p_3 \approx -[\tfrac{1}{2}(a_2 + p_1) \pm \sqrt{K_2/3}]$$

When large terms cancel in one root use the formula $p_1p_2p_3 = -a_0$.

$$\left[\text{Check that } \left(\frac{1}{p_1}+\frac{1}{p_2}+\frac{1}{p_3}\right) = -\frac{a_1}{a_0}\right]$$

(b) If $|K_3| > 0{\cdot}001$ proceed to stage (iii).

(iii) Calculate to five figures

$$K = \sqrt[3]{K_1/2} \text{ and also } K^2$$

(a) If $0{\cdot}0156 \leqslant K_3 \leqslant 0{\cdot}125$, calculate by slide-rule

$$\delta = (K_2 - K^2)/3K^2$$

and also

$$\alpha \simeq -2(1+\delta)$$

$$\beta, \gamma \simeq [-\tfrac{1}{2}\alpha \pm \sqrt{3\delta}(1 - \delta/6)]$$

When two large terms almost cancel use the formula $\alpha\beta\gamma = -2$.

[Check that $(\alpha + \beta + \gamma) = 0$].

(b) If K_3 is not within the range (a), compute

$$\lambda = 1/\sqrt[3]{K_3}$$

and determine α from Figs. 1 or 2.

Calculate by slide-rule

$$\beta, \gamma = -\tfrac{1}{2}[\alpha \pm \sqrt{\lambda + 6/\alpha}]$$

When these two terms almost cancel use the formula $\alpha\beta\gamma = -2$.

[Check that $(\alpha + \beta + \gamma) = 0$].

(c) The three roots are:

$p_1 = -\tfrac{1}{3}(K\alpha + a_2)$, $p_2 = -\tfrac{1}{3}(K\beta + a_2)$,

$p_3 = -\tfrac{1}{3}(K\gamma + a_2)$.

[Check that $p_1p_2p_3 = -a_0$].

Quartic Routine:—

Write the equation in the form:

$$[p^4 + a_3p^3 + a_2p^2 + a_1p + a_0] = 0$$

and proceed as follows:—

(i) Calculate accurately:

$$J_1 = [288a_0a_2 - 108a_0a_3{}^2 + 36a_1a_2a_3 - 108a_1{}^2 - 8a_2{}^3]$$

$$J_2 = (12a_0 - 3a_1a_3 + a_2{}^2)$$

(ii) Determine

$$J_3 = \sqrt[3]{J_1}$$

and $\quad \lambda = 12J_2/J_3{}^2$

(iii) Determine α from Figs. 1 or 2 if $|\lambda| \leqslant 10$, or from $\alpha \approx 2/\lambda$ if $|\lambda| > 10$.

Calculate $z = \alpha J_3/4$.

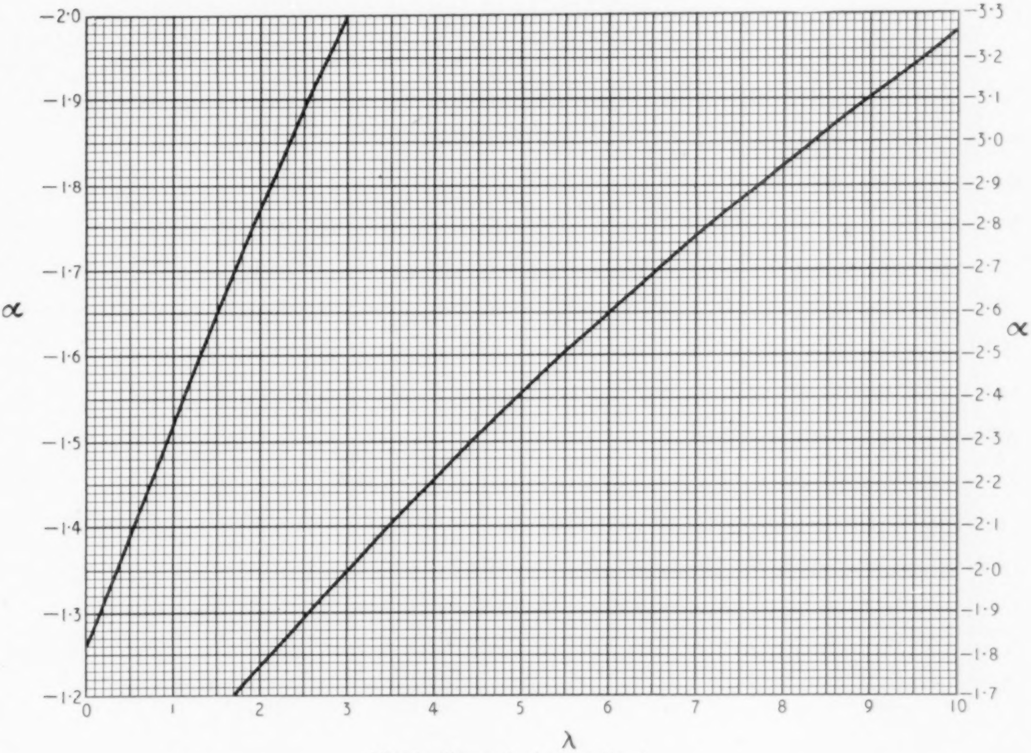

Fig. 2. *The root α for negative λ.*

(iv) Calculate

$$M = \left(a_3{}^2 - \tfrac{8}{3}a_2 + \tfrac{8}{3}z\right)^{\frac{1}{2}}$$

and $$N = [(a_2 + 2z)^2 - 36a_0]^{\frac{1}{2}}$$

If the difference of like terms occurs use the formula $MN = [a_2a_3 - 6a_1 + 2a_3z]$.

(v) Calculate

$$A_1 = (a_3 + M) \text{ and } A_2 = (a_3 - M)$$

If two terms cancel use the formula

$$A_1A_2 = \tfrac{8}{3}(a_2 - z)$$

(vi) Calculate

$$B_1 = (a_2 + 2z + N) \text{ and}$$
$$B_2 = (a_2 + 2z - N)$$

If cancellation occurs use the formula

$$B_1B_2 = 36a_0$$

(vii) The quadratic factors of the quartic are then:

$$(p^2 + \tfrac{1}{2}A_1p + \tfrac{1}{6}B_1)(p^2 + \tfrac{1}{2}A_2p + \tfrac{1}{6}B_2) = 0$$

[Check that $(A_1B_2 + A_2B_1) = 12a_1$]

Note that in the above routine the alternative formulae for use when cancellation occurs may also be used for checking.

The organization of the quartic routine on the same basis as the cubic routine introduces so much complication that the method loses its simplicity. Computational difficulties should, however, be rarely encountered in the above procedure. They may arise when $z \approx a_2$, corresponding to very slight damping, if the damping coefficient is required accurately; the requirement can then be met by improving the accuracy in α via Equ. (19) and working to more than three figures, five normally being adequate in such extreme cases. Difficulty may also arise when a_0 is very small compared with all the other coefficients, and in such a case it is a simple matter to determine one root by reversion or successive approximations and then to reduce the equation to a cubic by dividing out this root. In the author's experience practical cases in circuit design do not give rise to difficulties in the above routine.

6. Illustrations

A few difficult cases will be given below to illustrate the success of the method.

Example 1

A damped, slightly oscillatory circuit might give rise to the equation

$$[p^3 + 4p^2 + 5{\cdot}01p + 2{\cdot}02] = 0$$

the roots being

$$p_1 = -2, \quad p_2, p_3 = (-1 \pm 0{\cdot}1j)$$

The routine is:

(i) $K_1 = [180{\cdot}36 - 128 - 54{\cdot}54] = -2{\cdot}18$

$K_2 = (16 - 15{\cdot}03) = 0{\cdot}97$

(ii) $K_3 = 4{\cdot}74/108 \times 0{\cdot}912 = 0{\cdot}0482$ (slide-rule)

(iii) $K = -(1{\cdot}09)^{1/3} = -1{\cdot}0291$ (Barlow).

(a) $\delta = (0{\cdot}97 - 1{\cdot}0590)/3{\cdot}18 = -0{\cdot}0280$ (slide-rule)

$\alpha = -1{\cdot}944$

$\beta, \gamma = [0{\cdot}972 \pm j\,0{\cdot}290]$ (slide-rule)

(c) $p_1 = -2{\cdot}00,\ p_2, p_3 = (-1{\cdot}00 \pm 0{\cdot}0998j)$

This example demonstrates the need for calculating K_1 and K_2 accurately, and also shows that an accurate value of K may be necessary to determine δ with sufficient precision.

It will be found that the solutions of damped oscillatory circuits with a heavily-damped transient follow the same course. For example, the equation

$$[p^3 + 12p^2 + 22p + 20] = 0$$

with the roots $p_1 = -10,\ p_2,\ p_3 = (-1 \pm j)$. Widely separated roots also yield a similar value of K_3 as in the equation

$$[p^3 + 11{\cdot}1p^2 + 11{\cdot}1p + 1] = 0$$

with the roots $p_1 = -10,\ p_2 = -1,\ p_3 = -0{\cdot}1$.

Example 2

A slightly damped, oscillatory circuit with a slow transient gives rise to a different type of solution. The equation

$$[p^3 + 0{\cdot}12p^2 + 1{\cdot}0021p + 0{\cdot}10001] = 0$$

possesses the roots

$$p_1 = -0{\cdot}1,\ p_2, p_3 = (-0{\cdot}01 \pm j).$$

The routine is:

(i) $K_1 = [1{\cdot}082268 - 0{\cdot}003456 - 2{\cdot}70027] = -1{\cdot}6215$

$K_2 = (0{\cdot}0144 - 3{\cdot}0063) = -2{\cdot}9919$

(ii) $K_3 = -2{\cdot}63/(108 \times 26{\cdot}8) = -0{\cdot}000911$ (slide-rule)

(a) $p_1 = -[0{\cdot}04 + 0{\cdot}0604] = -0{\cdot}100$

$p_2, p_3 = (-0{\cdot}010 \pm j\,0{\cdot}999)$ (slide-rule)

High accuracy in K_1 and K_2 is needed in this case to obtain an accurate value for the real part of the complex roots.

Example 3

As a final example in the cubic equation, consider an equation yielding two roots of like magnitude and a very small root, such as:

$$[p^3 + 3{\cdot}01p^2 + 2{\cdot}03p + 0{\cdot}02] = 0$$

which has the roots $p_1 = -1,\ p_2 = -2,\ p_3 = -0{\cdot}01$.

The routine is:

(i) $K_1 = [54{\cdot}9927 - 54{\cdot}541802 - 0{\cdot}54]$
$= -0{\cdot}089102$

$K_2 = (9{\cdot}0601 - 6{\cdot}09) = 2{\cdot}9701$

(ii) $K_3 = 0{\cdot}00000327$ (slide-rule)

(a) $p_1 = -(1{\cdot}00333 - 0{\cdot}00333)$
$= -1{\cdot}00000$

$p_2 = -(1{\cdot}505 - 0{\cdot}500 + 0{\cdot}995)$
$= -2{\cdot}000$

$p_3 = -0{\cdot}02/2{\cdot}000 = -0{\cdot}01000$
(slide-rule)

Here the cancellation of like terms in the formula for p_3 makes the rounding-off errors large in the final result. The term $0{\cdot}995$ in p_2 is a rounding-off of $\sqrt{0{\cdot}99003} = 0{\cdot}994987$, and the fact that an accurate answer for p_3 would result in this case from the normal formula is a consequence of the unusually small value of K_3. It is wisest to use the formula $p_1 p_2 p_3 = -a_0$, as above. It might be observed that K_3 is not always small with this type of equation. If p_1 had been -3 instead of -1, then $K_1 = 19{\cdot}6715$ and $K_2 = 6{\cdot}9501$, thus changing the character of the solution.

Example 4

Since the quartic routine follows only one course, one example should be adequate for illustration. In some highly critical cases more accuracy may be necessary, but the following working has been performed on a slide-rule except for stage (i) where ordinary arithmetic was used, and for the calculation of J_3 which came from Barlow's tables.

In spite of this, only 2% error has arisen in the real part of the complex roots, although this is small in comparison with the imaginary part, and λ is near to the critical value of 3. The equation, which corresponds to a circuit giving rise to slightly-damped oscillations and a rapid transient, is

$$[p^4 + 16{\cdot}2p^3 + 64{\cdot}21p^2 + 28{\cdot}16p + 60{\cdot}6] = 0$$

The exact roots are $p_1 = -6$, $p_2 = -10$, $p_3, p_4 = (-0{\cdot}1 \pm j)$.

The procedure is:

(i) $J_1 = [1120600 - 1717600 + 1054500$
$- 85600 - 2117900] = -1746000$

$J_2 = [727{\cdot}2 - 1368{\cdot}6 + 4122{\cdot}9] = 3482.$

(ii) $J_3 = -120{\cdot}4$

$\lambda = 41784/14500 = 2{\cdot}88$

(iii) From Fig. 2: $\alpha = -1{\cdot}97$; $z = 59{\cdot}5$.

(iv) $M = 15{\cdot}8$ $N = 177$

(v) $A_1 = 32$ $A_2 = 0{\cdot}392$

(vi) $B_1 = 360$ $B_2 = 6{\cdot}06$

(vii) The quadratic factors are

$$(p^2 + 16p + 60)\,(p^2 + 0{\cdot}196p + 1{\cdot}01) = 0$$

(viii) The roots are therefore

$p_1 = -6{\cdot}00,\quad p_2 = -10{\cdot}0$

$p_3, p_4 = (-0{\cdot}098 \pm 1{\cdot}00j)$

Note that the alternative formulae in stages (iv), (v) and (vi) should be used for checking.

7. Conclusion

In circuit analysis there are two stages, one of which is the determination of the roots, the second requiring partial fraction expansions in order to invert the Laplace transforms. Some useful inversions in connection with this latter aspect are appended.

The author is grateful to Standard Telecommunication Laboratories, Ltd., for permission to publish this paper.

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APPENDIX

In the following collection of Laplace transform pairs, Heaviside's and McLachlan's notations have been used. McLachlan writes

$$\phi(p) \subset f(t) \text{ or } f(t) \supset \phi(p)$$

where $\phi(p)$ is the Heaviside operational transform of $f(t)$ defined by

$$\phi(p) = p\int_0^\infty \epsilon^{-pt} f(t)\,dt$$

The following collection covers all cubic and quartic transforms likely to be met in circuit design, others being obtainable from them by special substitutions if required.

Cubic Transforms

$$(1)\quad \frac{(\lambda p^3 + \mu p^2 + \nu p)}{(p+\alpha)(p+\beta)(p+\gamma)} \subset \left[\epsilon^{-\alpha t}\frac{(\lambda\alpha^2 - \mu\alpha + \nu)}{(\alpha-\beta)(\alpha-\gamma)} + \epsilon^{-\beta t}\frac{(\lambda\beta^2 - \mu\beta + \nu)}{(\beta-\alpha)(\gamma-\alpha)} + \epsilon^{-\gamma t}\frac{(\lambda\gamma^2 - \mu\gamma + \nu)}{(\gamma-\alpha)(\gamma-\beta)}\right]$$

$$(2)\quad \frac{(\lambda p^3 + \mu p^2 + \nu p)}{[(p+\alpha)^2 + \beta^2](p+\gamma)} \subset \left[\epsilon^{-\gamma t}\frac{(\lambda\gamma^2 - \mu\gamma + \nu)}{[(\alpha-\gamma)^2 + \beta^2]} + \epsilon^{-\alpha t}\cos(\beta t)\left\{\lambda - \frac{(\lambda\gamma^2 - \mu\gamma + \nu)}{[(\alpha-\gamma)^2 + \beta^2]}\right\} + \frac{1}{\beta}\epsilon^{-\alpha t}\sin(\beta t)\left\{\mu - \lambda(\alpha+\gamma) - \frac{(\alpha-\gamma)(\lambda\gamma^2 - \mu\gamma + \nu)}{[(\alpha-\gamma)^2 + \beta^2]}\right\}\right]$$

$$(3)\quad \frac{(\lambda p^3 + \mu p^2 + \nu p)}{(p+\alpha)^2(p+\beta)} \subset \left[\epsilon^{-\beta t}\frac{(\lambda\beta^2 - \mu\beta + \nu)}{(\alpha-\beta)^2} + \epsilon^{-\alpha t}\left\{\frac{[\alpha\lambda(\alpha-2\beta) + \mu\beta - \nu]}{(\alpha-\beta)^2} - t\frac{(\lambda\alpha^2 - \mu\alpha + \nu)}{(\alpha-\beta)}\right\}\right]$$

$$(4)\quad \frac{(\lambda p^3 + \mu p^2 + \nu p)}{(p+\alpha)^3} \subset \epsilon^{-\alpha t}\{\lambda + t(\mu - 2\lambda\alpha) + \tfrac{1}{2}t^2(\lambda\alpha^2 - \mu\alpha + \nu)\}$$

Quartic Transforms

$$(1)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p+\alpha)(p+\beta)(p+\gamma)(p+\delta)} \subset \Bigg[\epsilon^{-\alpha t}\frac{(-\lambda\alpha^3 + \mu\alpha^2 - \nu\alpha + \rho)}{(\beta-\alpha)(\gamma-\alpha)(\delta-\alpha)} + \epsilon^{-\beta t}\frac{(-\lambda\beta^3 + \mu\beta^2 - \nu\beta + \rho)}{(\alpha-\beta)(\gamma-\beta)(\delta-\beta)}$$
$$+ \epsilon^{-\gamma t}\frac{(-\lambda\gamma^3 + \mu\gamma^2 - \nu\gamma + \rho)}{(\alpha-\gamma)(\beta-\gamma)(\delta-\gamma)} + \epsilon^{-\delta t}\frac{(-\lambda\delta^3 + \mu\delta^2 - \nu\delta + \rho)}{(\alpha-\delta)(\beta-\delta)(\gamma-\delta)}\Bigg]$$

$$(2)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p+\alpha)(p+\beta)[(p+\gamma)^2+\delta^2]} \subset \Bigg[\epsilon^{-\alpha t}\frac{(-\lambda\alpha^3 + \mu\alpha^2 - \nu\alpha + \rho)}{(\beta-\alpha)[(\gamma-\alpha)^2+\delta^2]} + \epsilon^{-\beta t}\frac{(-\lambda\beta^3 + \mu\beta^2 - \nu\beta + \rho)}{(\alpha-\beta)[(\gamma-\beta)^2+\delta^2]}$$
$$+ \frac{\epsilon^{-\gamma t}\cos(\delta t)}{[(\alpha-\gamma)^2+\delta^2][(\beta-\gamma)^2+\delta^2]}\left\{\begin{array}{l}(\alpha+\beta-2\gamma)[\lambda\gamma(\gamma^2-3\delta^2) - \mu(\gamma^2-\delta^2) + \nu\gamma - \rho] \\ \quad + [(\alpha-\gamma)(\beta-\gamma) - \delta^2][\lambda(3\gamma^2-\delta^2) - 2\mu\gamma + \nu]\end{array}\right\}$$
$$+ \frac{\epsilon^{-\gamma t}\sin(\delta t)}{\delta[(\alpha-\gamma)^2+\delta^2][(\beta-\gamma)^2+\delta^2]}\left\{\begin{array}{l}\delta^2(\alpha+\beta-2\gamma)[\lambda(3\gamma^2-\delta^2) - 2\mu\gamma + \nu] \\ \quad - [(\alpha-\gamma)(\beta-\gamma) - \delta^2][\lambda\gamma(\gamma^2-3\delta^2) - \mu(\gamma^2-\delta^2) + \nu\gamma - \rho]\end{array}\right\}\Bigg]$$

$$(3)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{[(p+\alpha)^2+\beta^2][(p+\gamma)^2+\delta^2]} \subset \frac{1}{\{[(\alpha-\gamma)^2+\beta^2+\delta^2]^2 - 4\beta^2\delta^2\}}$$
$$\times\Big[\epsilon^{-\alpha t}\cos(\beta t)\{2(\gamma-\alpha)[\lambda\alpha(\alpha^2-3\beta^2) - \mu(\alpha^2-\beta^2) + \nu\alpha - \rho] + [(\alpha-\gamma)^2+\delta^2-\beta^2][\lambda(3\alpha^2-\beta^2) - 2\mu\alpha + \nu]\}$$
$$+ \frac{1}{\beta}\epsilon^{-\alpha t}\sin(\beta t)\{2\beta^2(\gamma-\alpha)[\lambda(3\alpha^2-\beta^2) - 2\mu\alpha + \nu] - [(\alpha-\gamma)^2+\delta^2-\beta^2][\lambda\alpha(\alpha^2-3\beta^2) - \mu(\alpha^2-\beta^2) + \nu\alpha - \rho]\}$$
$$+ \epsilon^{-\gamma t}\cos(\delta t)\{2(\alpha-\gamma)[\lambda\gamma(\gamma^2-3\delta^2) - \mu(\gamma^2-\delta^2) + \nu\gamma - \rho] + [(\alpha-\gamma)^2+\beta^2-\delta^2][\lambda(3\gamma^2-\delta^2) - 2\mu\gamma + \nu]\}$$
$$+ \frac{1}{\delta}\epsilon^{-\gamma t}\sin(\delta t)\{2\delta^2(\alpha-\gamma)[\lambda(3\gamma^2-\delta^2) - 2\mu\gamma + \nu] - [(\alpha-\gamma)^2+\beta^2-\delta^2][\lambda\gamma(\gamma^2-3\delta^2) - \mu(\gamma^2-\delta^2) + \nu\gamma - \rho]\}\Big]$$

$$(4)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{[(p+\alpha)^2+\beta^2]^2} \subset \frac{1}{2\beta^3}\epsilon^{-\alpha t}\Big[\cos(\beta t)\{2\lambda\beta^3 + \beta t[\lambda\alpha(\alpha^2-3\beta^2) - \mu(\alpha^2-\beta^2) + \nu\alpha - \rho]\}$$
$$- \sin(\beta t)\{[\lambda\alpha(\alpha^2+3\beta^2) - \mu(\alpha^2+\beta^2) + \nu\alpha - \rho] - \beta^2 t[\lambda(3\alpha^2-\beta^2) - 2\mu\alpha + \nu]\}\Big]$$

$$(5)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p^2+\alpha^2)(p^2+\beta^2)} \subset \frac{1}{(\beta^2-\alpha^2)}\Big\{(\nu - \alpha^2\lambda)\cos(\alpha t)$$
$$+ \left(\frac{\rho}{\alpha} - \alpha\mu\right)\sin(\alpha t) - (\nu - \beta^2\lambda)\cos(\beta t) - \left(\frac{\rho}{\beta} - \beta\mu\right)\sin(\beta t)\Big\}$$

$$(6)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p^2+\alpha^2)^2} \subset \left\{\lambda\cos(\alpha t) + \frac{(\rho+\mu\alpha^2)}{2\alpha^3}\sin(\alpha t) + \frac{(\nu-\alpha^2\lambda)}{2\alpha}t\sin(\alpha t) - \frac{(\rho-\alpha^2\mu)}{2\alpha^2}t\cos(\alpha t)\right\}$$

$$(7)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p+\alpha)^2(p+\beta)^2} \subset \frac{1}{(\beta-\alpha)^3}\Big[\epsilon^{-\alpha t}\{[\lambda\alpha^2(3\beta-\alpha) - 2\mu\alpha\beta + \nu(\alpha+\beta) - 2\rho] - t(\beta-\alpha)(\lambda\alpha^3 - \mu\alpha^2 + \nu\alpha - \rho)\}$$
$$- \epsilon^{-\beta t}\{[\lambda\beta^2(3\alpha-\beta) - 2\mu\alpha\beta + \nu(\alpha+\beta) - 2\rho] - t(\beta-\alpha)(\lambda\beta^3 - \mu\beta^2 + \nu\beta - \rho)\}\Big]$$

$$(8)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p+\alpha)^3(p+\beta)} \subset \Bigg[\epsilon^{-\beta t}\frac{(\lambda\beta^3 - \mu\beta^2 + \nu\beta - \rho)}{(\beta-\alpha)^3} - \epsilon^{-\alpha t}\Bigg\{\frac{[\lambda\alpha(\alpha^2 - 3\alpha\beta + 3\beta^2) - \mu\beta^2 + \nu\beta - \rho]}{(\beta-\alpha)^3}$$
$$- \frac{t}{(\beta-\alpha)^2}[\lambda\alpha^2(3\beta-2\alpha) - \mu\alpha(2\beta-\alpha) + \nu\beta - \rho] + \frac{t^2}{2(\beta-\alpha)}(\lambda\alpha^3 - \mu\alpha^2 + \nu\alpha - \rho)\Bigg\}\Bigg]$$

$$(9)\quad \frac{(\lambda p^4 + \mu p^3 + \nu p^2 + \rho p)}{(p+\alpha)^4} \subset \epsilon^{-\alpha t}\left\{\lambda - t(3\lambda\alpha - \mu) + \tfrac{1}{2}t^2(3\lambda\alpha^2 - 2\mu\alpha + \nu) - \tfrac{1}{6}t^3(\lambda\alpha^3 - \mu\alpha^2 + \nu\alpha - \rho)\right\}$$

When transforms arise which contain a constant term in the numerator, or an inverse power of p as a factor, it is a simple matter to rearrange the transform into the form given above. The general formula is

$$\left\{\frac{\ldots + A_n p^n + \ldots + A_3 p^3 + A_2 p^2 + A_1 p + A_0}{\ldots + a_n p^n + \ldots + a_3 p^3 + a_2 p^2 + a_1 p + a_0}\right\} = \left\{\frac{A_0}{a_0} + \left[\frac{\ldots + B_n p^n + \ldots + B_3 p^3 + B_2 p^2 + B_1 p}{\ldots + a_n p^n + \ldots + a_3 p^3 + a_2 p^2 + a_1 p + a_0}\right]\right\}$$

where $B_n = (A_n - A_0 a_n/a_0)$. If an inverse power of p exists outside, then the above rearrangement can be repeated until the desired form appears; the constant term A_0/a_0 will then become a polynomial in inverse powers of p. This procedure is generally less laborious and more straightforward than integration. When the numerator is of higher degree than the denominator, simple division will reduce it.

L.F. NOISE IN RESISTORS

Excited by R.F. Current

By Noel B. Montagnon

(Concluded from p. 263 *October issue)*

Calculation of the Calibrator Diode Load

IN this measurement, the noise from the test resistor was never measured directly. This would have required a great deal of calculation with little hope of accuracy owing to the many factors such as amplifier gain and bandwidth, detector response, etc., which affect the signal as it is displayed by the indicating equipment. Instead, a deflection D_x was obtained for the test resistor at a given excitation and for a given gain and a second deflection D_k (D_k approximately equal to D_x) from a standard noise source with the same gain setting.* The ratio D_x/D_k is calculated and is multiplied by the known noise output of the standard source. The standard is thus used as a calibrator for the measuring equipment.

The calibrator used in this equipment was a special diode (CV172), designed as a predictable noise source when operated in the temperature-limited condition. Its output in mean-square noise volts per unit bandwidth is given by the following equation:

$$\bar{e}^2 = 2\epsilon I_d(R_d)^2$$

where ϵ is the electronic charge, I_d is the mean direct current flowing in the diode and R_d is the load resistance across which the noise voltage is developed. This load resistance is primarily a resistor in the d.c. anode circuit, but this d.c. load is shunted by the impedance which is normally present at the test position. In fact, in order to keep the impedance at the test position as nearly the same as it was in the case of the resistor under test, a dummy 'diode load' is inserted in the test position. This consists of a 'noiseless' resistor of the same value as the test resistor and a blocking capacitor to prevent the flow of direct current in this resistor.

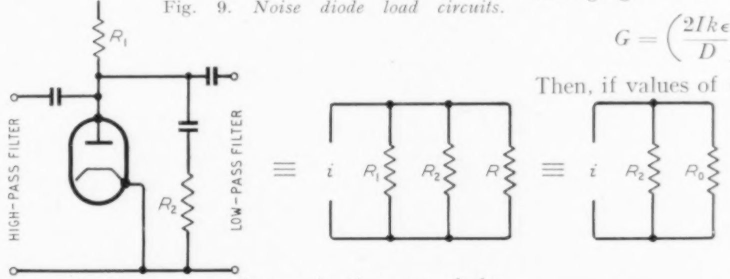

Fig. 9. *Noise diode load circuits.*

For the calibrator to be of any use, the value of R_d must be known at least as accurately as the desired accuracy of the final measurement. In this circuit the value could not be calculated directly and instead a figure was determined from several measurements. Fig. 9 shows equivalent circuits of the diode and its load which will be used in the explanation of two of these methods.

R_1 is the resistor in the d.c. supply line across which the noise voltages are developed by the fluctuating current from the diode. R_2 is the dummy load which, with its blocking capacitor, is installed in place of the test resistor. R is the effective resistive component of the rest of the circuit (filters, etc.).

The first method was suggested by the variation of the noise output for constant diode current when the value of R_2 was varied. In one of the first tests, calibration readings were taken for four different values of R_2. The diode current was adjusted in each case to give a constant deflection of the galvanometer. In a separate test it was found that the deflection was directly proportional to the diode current for fixed gain and load resistance. This leads to the expression:

$$D = k\bar{e}^2 = 2k\epsilon I\left(\frac{1}{G + G_0}\right)^2$$

where D is the deflection, k is a constant depending on gain, etc., G is the conductance of R_2 and G_0 is the conductance of R and R_1 in parallel. Rearranging:

$$G = \left(\frac{2Ik\epsilon}{D}\right)^{1/2} - G_0$$

Then, if values of G are plotted against $(I)^{1/2}$ as in Fig. 10, a curve is produced whose intercept on the G-axis is G_0. The six curves shown were plotted from data taken during a test run on an I.R.C. resistor and the amplifier gain was changed for each frequency of excitation. This explains the increase of slope with exciting frequency. The intercept value for R_0 ($= 1/G_0$) is between 18 and 19·5 kΩ.

A second method, involving the ratio of deflections at constant diode current with variation in R_1, was used. If two deflections D_1 and D_2 are obtained with values for R_1 of R'

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* D_x and D_k are the differences between the deflections for total noise and those for background (thermal, etc.) at the same gain.

and aR' respectively, then:

$$D_1 = 2k_1\epsilon I\left(\frac{RR'}{R+R'}\right)^2$$

$$D_2 = 2k_2\epsilon I\left(\frac{RaR'}{R+aR'}\right)^2$$

and $$D_1/D_2 = k_1/k_2\left(\frac{R+aR'}{a(R+R')}\right)^2$$

therefore $$R = \frac{aR'(1-\sqrt{D_1k_2/D_2k_1})^{\dagger}}{a\sqrt{D_1k_2/D_2k_1}-1}$$

This method is not particularly accurate since the ratio of deflections is nearly equal to unity in most cases. This leads to an error of 25% for an error in deflection of 5%. It gives, however, a range of value for R with a mean of approximately 24 kΩ. This is in fair agreement with the value obtained above for R_0 since R_0 is the resultant of R in parallel with 100 kΩ.

Finally, a direct measurement of the impedance was made at several frequencies with a Schering bridge. A 10-kΩ resistor in series with 0·05 μF was installed for R_2 and, with this, the magnitude of the impedance at the centre frequency of the amplifier band was 6·6 kΩ. This represents a value of approximately 19·5 kΩ for R_0.

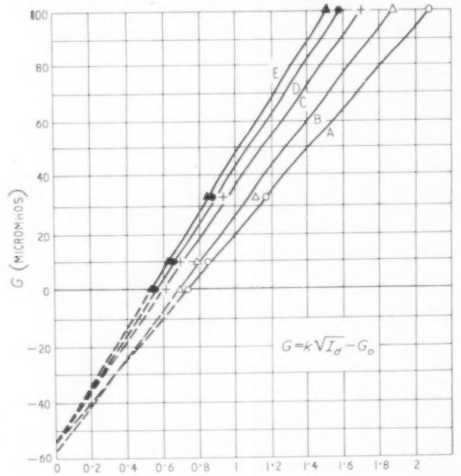

Fig. 10. *Graphical determination of the noise diode loading conductance* G_0 *of the external circuit;* $G_0 \approx 54$ *μmhos; k is a function of amplifier gain, it thus varies with frequency. A, curve for* 60-*kc/s setting; B, for* 100 *kc/s; C, for* 200 *kc/s; D, for* 300 *and* 500 *kc/s and E for* 1,000 *kc/s.*

Measurements Carried Out

A series of observations was carried out with the equipment as described on the group of resistors in Table 3. These observations were made at seven frequencies between 50 kc/s and 5 Mc/s and, wherever significant deflections were obtained, at three levels of excitation.

TABLE 3

RESISTORS USED IN FINAL OBSERVATIONS

1. IRC BTA 1/2W, 10 kilohms
2. ,, ,, ,, ,, ,,
3. ,, ,, ,, ,, ,,
4. ,, ,, ,, ,, ,,
5. Stackpole ,, ,, ,,
6. Welwyn 1W, ,, ,, , Pyrolytic
7. Continental Carbon 'Nobelloy', 10 kilohms

In these tests, the current noise for all the resistors at all excitation levels was observed and recorded, along with the gain setting of the amplifier for each test. After a complete set of current-noise readings for one frequency had been made the test resistor was replaced by the dummy diode load and a set of calibration readings was made. In each case the gain setting corresponding to the particular measurement was used in the calibration.

This arrangement, while it separated the first current–noise measurement from its calibration by an interval of some hours, was found to be the most efficient. The time lapse did not appear to affect the accuracy of the measurement. This was probably true since the gain resetting with the stepped control was quite accurate and the various supplies were very stable. The virtue of the method was in the saving of time it allowed. A considerable time was always necessary for the warming up of the exciter and the calibrator controls, particularly the latter, and, by performing all the calibration readings at once, this warming up time appeared only once for each set.

This group of resistors was chosen for several reasons. First, the resistance value; the filters were designed for a test resistor of approximately 10 kΩ. Higher values are too heavily loaded by the external circuit and lower values load the exciter too heavily. Actually, measurements could be made on resistors ranging from 3·3 to 33 kΩ, but without as much flexibility. Then, the sensitivity range of the amplifier was rather narrow. This was selected for the noise level of the I.R.C. type of resistor. This type has a noise level about in the middle of the range of the eight types tested by Pavich and it also gives a relatively stable output. The Erie type was tested, but this gave excessive voltages for the existing setting. This type, according to Pavich, yields the next highest noise output to the I.R.C. type. Other

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[†] To eliminate the ratio k_1/k_2, the gain is kept constant, or k_1, k_2 may be determined by some other measurement.

types giving lower noise outputs, such as the Stackpole and Allen-Bradley, were tested, and readable deflections were produced by the Stackpole, but not by the Allen-Bradley, Welwyn and Nobelloy types, all of which have very low noise outputs. This is to be expected since the filter elements consist of Welwyns and these must contribute something to the system noise and thus tend to mask the noise from a test resistor of the same general characteristic.

In these measurements, each deflection value is the average of 100 instantaneous deflection readings taken at 2-second intervals. There are four of these values for each observation and calibration and it can easily be seen that it was a matter of many hours of work to obtain a complete observation at one excitation frequency.

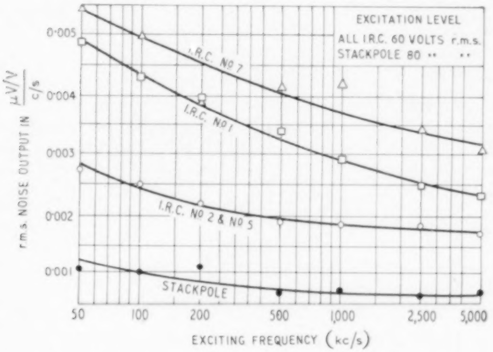


Fig. 11. *Noise output versus exciting frequency for five 10-kΩ ½-W resistors.*

Observations and Results

The noise output of the five resistors giving significant readings with the final equipment are plotted in the curves of Fig. 11. The semi-logarithmic plot of r.m.s. noise volts per volt per cycle bandwidth is used to show the curvature to the best advantage. It also helps to show the relationship of this noise to the d.c. noise output. For the resistors designated as numbers 2 and 5, the noise level for d.c. excitation in the same units is approximately 0·010 μV, but at 50 kc/s it is less than 0·003 μV.

All the curves show the same general slope—a drop from the d.c. level with increasing excitation frequency and a tendency to reach a constant level at a frequency between 2 and 5 Mc/s. The curve for resistor No. 7 is particularly interesting. In this figure, the resistor is shown to have the highest noise output but, at the beginning of the tests on the equipment, it gave a curve indistinguishable from that shown for resistors Nos. 2 and 5. During the four months over which the tests and subsequent measurements took place, however, its noise output increased to the value shown here.

The three highest curves, for the four I.R.C. resistors, are plotted from data obtained with an excitation of 60 V. The Stackpole resistor, which produced lower noise voltages for d.c. excitation, gave significant results only at an excitation of 80 V.

In Fig. 12, a logarithmic plot of mean-square noise volts per unit bandwidth versus exciting frequency is used so that an approximate value of the thermal noise can be included. This is chiefly included to show that the current noise becomes independent of exciting frequency at a value considerably higher than the thermal level. The thermal level was calculated on the basis of an input resistance of 100 kΩ to the first stage of the noise amplifier. This input resistance is calculated from the actual input grid resistor shunted by the transfer and output impedances of the parallel-T in parallel. The impedances of the low-pass filter and the test resistor are in series with the parallel-T transfer impedance, but are negligible in comparison to it. The value of 100 kΩ is probably not more than 10% in error.

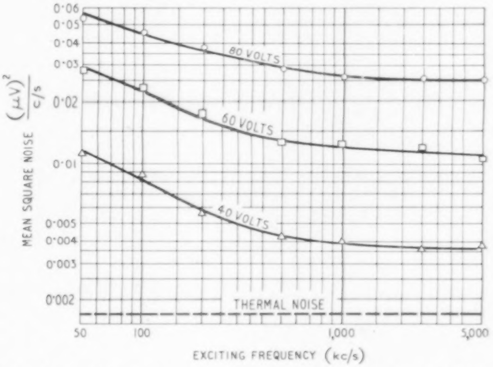
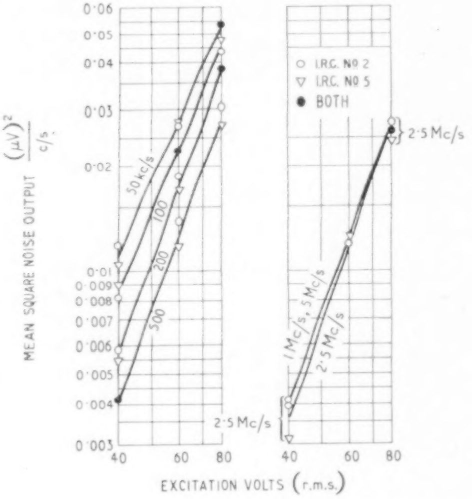


Fig. 12. *Noise output of I.R.C. No. 2 and No. 5 (mean) at three excitation levels.*

The three curves of this figure are plotted for resistors Nos. 2 and 5 for excitation levels of 40, 60 and 80 V. Slopes taken from these curves in the region between 50 and 100 kc/s have values of −0·54, −0·40 and −0·34 respectively. These slope values are very nearly inversely proportional to the two-thirds power of the ratio of the exciting voltages.

Fig. 13 presents a set of curves for the same two resistors with mean-square noise volts per unit bandwidth plotted against exciting voltage. The slopes of these curves indicate that the noise is dependent not on the square of the applied voltage as it is in the d.c. case, but on a higher power. A table included in the figure gives the values of the slopes of the curves plotted for different exciting frequencies. This table shows that the voltage index rises from 2·26 to 2·75 over the frequency range of 50 to 500 kc/s and then remains fairly constant at approximately 2·75.



CURVE	50 kc/s	100 kc/s	200 kc/s	500 kc/s	1 Mc/s, 5 Mc/s	2·5 Mc/s
SLOPE	2·26	2·43	2·75	2·76	2·74	2·85

Fig. 13. *These curves show that the noise depends on a higher power than the square of the applied voltage.*

The results of the measurements at 20 kc/s (see Fig. 3), while not adequate for a detailed discussion, are worthy of mention as they offer some confirmatory evidence. They show a similar tendency in frequency dependence, as the noise level is lower at 500 kc/s than it is at 100. The noise output is well below the d.c. level for the resistor tested, being reduced by a factor of approximately 2·5 at 100 kc/s and 6 at 500 kc/s. The actual noise levels cannot fairly be compared with those of the measurements at 5 kc/s as two new variables enter the relationship—the frequency of measurement and the resistance value. In this measurement, also, the voltage dependence is found to be greater than square law, the index being approximately 2·6 at 100 kc/s and 2·8 at 500 kc/s.

One further general observation was made—on the quality of the noise. In all the tests and measurements where the galvanometer was used as the indicating instrument, it was observed that the noise due to alternating current was considerably more erratic than that from direct current or the calibrating diode. The general motion of the galvanometer was always more violent in the a.c. case and the excursions from the mean deflection were greater. For example, while the usual maximum excursion from the mean in the case of shot noise was between 5 and 10% of the mean, that in the case of a.c. excitation was as high as 25%.

Discussion

From the viewpoint of providing a basis for a thorough theoretical discussion, the results of this investigation are inadequate. This, however, was not the plan at the outset of the experiment. In the beginning, the idea was to attempt to discover whether noise was generated by alternating current in the resistor and to find a method of measuring such noise if it existed. The results obtained successfully fulfil these requirements. They show beyond question the presence of noise voltages produced by alternating current and, further, they appear to show that this noise differs markedly from that produced by direct current.

In the matter of frequency dependence, there is an apparent departure from the behaviour shown in the d.c. case. The noise level falls from the d.c. value at much less than the inverse half power of the exciting frequency and then becomes independent of the frequency. The word 'apparent' is used as it is possible that a similar effect might be observed in the d.c. case if the frequency of measurement were taken high enough. Earlier investigators do not appear to have explored beyond 1 Mc/s.

Such an effect may not be observed, however, as there are at least two respects in which the behaviour of the resistor can vary from the d.c. case. These are the skin effect, in which the current is forced more and more into the outer layers of the resistance material as the frequency increases, and the effect in which the resistor appears to behave like a resistance-capacitance combination. In the latter case the effective resistance is greatly reduced from its d.c. value at a frequency of a few megacycles.

There is some rather inconclusive evidence to the effect that the noise level, at very low exciting frequencies, is higher than that produced by direct current. When making measurements on d.c. noise it is generally necessary to wait for some minutes after the current is switched on to allow the noise to reach a stable level. If this is not done, the noise, in many cases, is found to be higher than that observed after a few minutes. In the early stages of the present investigation, when direct current was being used, a few trials were made on the effect of reversing the current after it had been flowing for a few minutes. In some of these tests, it was found that the noise level was higher after the current reversal than it had been immediately before. This did not occur at every trial and insufficient trials were made to decide whether the positive results were due to chance. This is mentioned, not as a claim of discovery of information, but as a direction for possible future study. It also shows a possible method in which noise from very low-frequency alternating or pulsating currents could be made without great changes in the measuring equipment used for the study of d.c. noise.

The manner in which this noise depends on the exciting voltage is another point of difference. The resistors used were the same as used by Pavich, for which he found a square-law dependence on applied voltage. Moreover, on some of the records taken at 20 kc/s measuring frequency, where noise for three d.c. excitations was recorded, the ratio of the deflections was proportional to the square of the applied voltage ratio to within 3%. Yet, with alternating current, the voltage index is found to be considerably greater than 2 and dependent on the exciting frequency up to the point where the noise itself becomes independent of frequency.

These differences in character of the noise from the two sources show that there is room for much further study on this subject. The dependence on exciting frequency must be studied at frequencies nearer to the exciting frequency and nearer to zero frequency. The d.c. noise output should be investigated at frequencies above 1 Mc/s. The effects of varying the measuring frequency and the resistance value must also be investigated before anything like the complete picture begins to appear.

In one feature the results of this experiment agree with those found by Pavich. This is in the relative noise production of the different types of resistors. At least in those types tested, the order remains the same.

The change in noise output of two of the composition-type resistors after long exposure to alternating current suggests another worthwhile line of study. This effect was observed in the I.R.C. resistor (number 7), used in the test position during all the early tests, and in the Allen-Bradley resistors used in the filters. No such change was observed in the Welwyn resistors which were used later and which were exposed for at least the same length of time. In both cases where the effect was observed, the exposure was for longer than 100 hours and the resistors were fully loaded. They became noticeably warm a few minutes after the current was switched on, but the temperature rise was never excessive. Tests should be carried out to determine the magnitude and rate of change of this effect and to discover whether the d.c. noise level is affected. Microscopic studies of the resistance compound, before and after the change, might shed some light and lead to better resistor design.

I would like to thank the Defence Research Board of Canada for its financial assistance, and Dr. R. A. Chipman, of the Radio Engineering Laboratory, McGill University, for his advice and assistance.

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CORRESPONDENCE

Letters to the Editor on technical subjects are always welcome. In publishing such communications the Editors do not necessarily endorse any technical or general statements which they may contain.

Rotating Observers

SIR,—Perhaps you will allow me to make three brief comments on Professor Howe's interesting Editorial in your September issue.

The first refers to the statement, at the foot of the first column on p. 224, in connection with unipolar induction by means of a cylindrical bar magnet rotating about its axis, that: "no one can have any doubt as to the source of the e.m.f."

I believe Professor Howe has made this, or a very similar, statement many, many times, but I am not aware that he has, on any occasion, provided a convincing proof of it.

The second point is in connection with the two observers, A and B, of his correspondent. If A is on a charged circle, and B is moving about the same axis with the same angular velocity, Professor Howe says: "the charge on A appears (to B) to be at rest and the magnetic field presumably vanishes so far as B is concerned". I do not think so: the magnetic field would vanish for B only if the laws of electromagnetism took the same form in each of two frames of reference, one of which is rotating. It is well known that this is not so, and if it were, then it would follow at once that a complete specification of the electric field of a rotating magnet, such as is shown in Fig. 3 of the Editorial, would be given by a theory which accepts the rotation of the whole of the magnetic field of the magnet with the same angular velocity. Such a theory is regarded by both Professor Howe and myself as false.

The third point arises out of the second. Professor Howe states that it seems to be very undesirable to regard electromagnetic phenomena from the point of view of a rotating observer. But unfortunately no other kind of observer has *ever* made any electromagnetic observations or experiments at all. We are *all* rotating observers, and shall remain so until we can equip an electromagnetic laboratory in a space ship which is propelled, by the latest refinements in servo-control, with uniform rectilinear velocity in the inertial system of the 'fixed' stars.

It is true, of course, that the angular velocity of the earth is very, very small in comparison with that of any rotating body in a laboratory experiment. But electromagnetism is a very exact science, and it puzzles me that a very exact mathematical theory for phenomena in inertial frames of reference has been built up from the evidence of experiments carried out in a *rotating* frame of reference, without, so far as I know, the possible implications of this inconsistency being studied and analysed.

E. G. CULLWICK.

Department of Electrical Engineering,
University of St. Andrews,
Dundee.
17th September 1954.

Harmonic Distortion and Negative Feedback

SIR,—In his article under the above heading, in your May issue, Zepler rightly showed that where an amplifier has a flat characteristic lying between two sloping portions, the overall linearity may be improved by negative feedback, but in his analysis of the curve which flattens off at each end, as in Fig. 2, which I assume to be symmetrical, he makes a misleading statement—namely that since P_1 is nearer than P to Q then " . . . the reduction of distortion is marked even for the flat portion of the curve."

Now Q is the point at which the tangent to both curves cuts the flat portion. It corresponds to $V_1 = 0{\cdot}3$ V without feedback and 3·0 V with feedback. Apart from this, it has no particular significance.

Since the usual criterion for making comparisons, namely that the output voltage must be the same with and without feedback, does not in this case lead to a unique solution in V_1, it is incorrect to draw any general conclusion from any two particular values.

What we can deduce from the curves is that over the range $V_0 = 0$ to 75 V, linearity is improved by feedback, but that at $V_0 = 75$ V, the amplifier cuts off and feedback does nothing to improve the distortion due to this.

R. O. ROWLANDS.

British Broadcasting Corporation,
Evesham, Worcs.
6th September 1954.

SIR,—Mr. Rowlands' point could easily be met by assuming that the part PQ in Fig. 2 is practically flat, i.e., that its gradient is infinitely small without being zero, but even if the gradient is zero there is no difficulty in making comparisons; one must then compare the conditions for equal effective input voltages. I do not think therefore that my statement is in any way misleading. With a given effective input of 0·3 V the curve OPQ (which is in fact one half of a symmetrical curve) can be made to approach the straight line OQ as closely as is desired, and hence feedback does improve distortion caused by the flat part.

There is a slight error in Fig. 2, owing to a last-minute alteration. The lower of the two scales of the X axis should read

0   0·2   0·4   0·6

instead of 0, 1, 2, 3, since

$1 + A_{av}\beta$ is assumed to be equal to 2.

E. E. ZEPLER.

University of Southampton,
22nd September 1954.

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British Standards Institution, 2 Park St., London, W.1.

NEW BOOKS

Electronics. Pp. 395 + viii. Price 32s. 6d.

Telecommunications. Pp. 454 + ix. Price 35s.

By A. T. Starr, M.A., Ph.D., M.I.E.E. Sir Isaac Pitman & Sons, Ltd., Parker Street, Kingsway, London, W.C.2.

A major difficulty in reviewing these two books is that the author nowhere indicates how much prior knowledge of the subjects he expects his readers to possess. The natural presumptions are that he expects his readers to be beginners and that he will include everything that they need to know. No more than a quick glance through "Electronics" and "Telecommunications" is necessary to discover that the author certainly does not begin at the beginning. He assumes a great deal of prior knowledge on the part of his readers and of a kind which is quite hard to describe, for it varies very much in its extent in different parts of the subjects.

The books are meant to cover the syllabi of Electronics and Telecommunications in the London University Degrees. They include a number of questions taken from past examination papers. Of these questions there is one which appears in both books. It is, "Show how a diode rectifier circuit can be arranged to provide automatic gain control in a superheterodyne radio receiver, and explain the action of the controlled variable-mu valves. What factors determine the efficacy of control?"

It is rather surprising to find such a question at all in "Electronics" and it is perhaps not unreasonable that neither a.g.c. nor the variable-mu valve should be mentioned in it. It is astounding that in "Telecommunications" neither of these things should be referred to; one would expect both to be very fully treated here.

It may be that the author assumes his readers to know about these things before they open his books. The reviewer feels, however, that the question should not be in "Electronics" at all and that a.g.c. and the variable-mu valve should be dealt with in "Telecommunications".

The author gives no warning that the two books are by no means complementary but are overlapping. An appreciable amount of material is the same, word for word, in both books. The outstanding example is the section on transmission lines and wave filters. There are 64 pages on them in "Telecommunications" and 50 of them are reproduced verbatim in "Electronics". There is no harm in this in itself, of course, but the author would have been wise to warn his readers of the duplication of material in the two books.

"Electronics" is divided into six chapters and seven appendices. The chapter headings are: Physical Fundamentals; Valves; Rectification; Circuit Theory; Amplifiers, oscillators and detectors; and Electronic applications. The appendices cover: Mathematical formulae; Steady-state a.c. theory; Fourier analysis; Power level—decibel, neper; Operational calculus—Laplace transform method; M.K.S. system—Maxwell's equations; and Noise.

The author's definition of 'electronics' is in agreement with modern thoughtful usage. He adopts an American definition which says that it is "that branch of science and technology which relates to the conduction of electricity through gases or in vacuo", but he extends it to cover "non-linear conductors and semi-conductors". This definition appears in the opening paragraph of Chapter 1, so that one would expect the book to be mainly about valves and analogous devices. It is not, however, for, in spite of the definition, the word is used to cover almost anything that the author wishes to drag in. A section on magslips and selsyns is included, for instance.

Except in certain pulse circuits, which are not referred to, transmission lines and wave filters have little connection with electronics in any sense of the word and yet over 50 pages are devoted to them. On the other hand, LC and sine-wave RC oscillators have together a total of three pages, class B amplifiers one page, and class C amplifiers a page and a half! These things are at the very heart of important industrial aspects of electronics (in its common sense)—r.f. heating, diathermy, etc.—and yet they are treated as insignificant compared with transmission lines and wave filters.

"Telecommunications" is divided into ten chapters and nine appendices. The chapter headings are: Communication systems; Elements of telegraph systems; Acoustics, microphones and reproducers; Elements of telephone systems, line and transmission networks; Telecommunication circuits; Line telephony, Basic principles of television; Electromagnetic waves, radiation and aerials; and Microwave technique. The appendices cover: Mathematical formulae; Steady-state a.c. theory; Fourier analysis; Power level: decibel: neper; Operational calculus: Laplace transform method; Star–mesh transformation; Distortion and time delay; Vectors: Maxwell's equations; and Waveguide theory.

This book has similar characteristics to "Electronics"; there is a lack of proportion in the choice of material and in the space allocated to it. Oscillators have four pages (including tuned-circuit, crystal and R.C.), the superheterodyne has three-quarters of a page, noise has seven pages and valves have nine and a half pages, but transmission lines and wave filters have 64 pages. There are great variations, too, in the form of treatment. In the case of telegraphy machines it comprises merely an elementary description of them; in the case of wave filters it is mathematical, involving hyperbolic functions.

Both books contain a great deal of information and there is no doubt at all that they will both form very useful reference books for engineers and technicians. "Electronics" is noteworthy in containing in its first chapter one of the best elementary accounts of physical fundamentals that we have seen. It is unusual in starting off with wave mechanics and quantum theory in quite an understandable way. W. T. C.

Magnetic Amplifier Circuits

By William A. Geyger. Pp. 277 + ix. McGraw-Hill Publishing Co., Ltd., 95 Farringdon Street, London, E.C.4. Price 42s. 6d.

It is only fair to the author to emphasize that this is a book on *circuits* for magnetic amplifiers, not on the theory of the transductors used in them. There is an introductory review of transductor theory, which deserves credit for the clear distinction between operation with 'natural' and with 'forced' magnetization, but the characteristics of load current versus supply voltage are plotted with the axes interchanged compared with the usual British practice.

The weakness of the book lies in the inadequate treatment of input and output impedances of the transductor. Nowhere is it pointed out that the output impedance can be deduced from graphical characteristics; on the one hand one may want to use a transductor without self-excitation (feedback) as a constant-current source, and on the other hand one cannot fairly assess the increased power gain of a self-excited amplifier without noting that the output impedance tends to zero as the self-excitation approaches 100%. It is also most misleading to state (p. 207) that the effective impedance of the control winding is merely its d.c. resistance, for if that were so there would be no problem of time-constant.

But the reader who has acquired elsewhere an under-standing of the mechanism of transductors will find this book an invaluable source of circuit arrangements, including the less-known ones employing a.c. instead of d.c. as the control power. The circuits are grouped according to number of reactors and feedback arrangements, e.g. Chapter 7 on 'Development of External-feedback Types of Magnetic-amplifier Circuits' is followed by Chapter 8 on 'Duodirectional External-feedback Circuits with Two Saturable-reactor Elements'; and flux-gate magnetometers, magnetic frequency-multipliers and second-harmonic magnetic modulators are all treated in appropriate places. The rather strange title of Chapter 15, 'Magnetic-amplifier Circuits of the Self-balancing Potentiometer Type', in fact refers to magnetic amplifier systems which are stabilized by overall negative feedback applied as voltage or current to the input circuit, while they usually have self-excitation (or positive feedback) applied to each magnetic-amplifier stage. The overall negative feedback provides the linearity and constancy of gain necessary for meter amplifiers, etc. The construction of the book as a catalogue of circuits, with here and there snippets of verbatim quotations from original papers, does not make for easy reading; and the reviewer was irritated by the use of the phrase 'properly rated' to mean 'of appropriate value' in reference to circuit components.

But besides being encyclopaedic in its own coverage of magnetic-amplifier circuits, the book includes extensive lists of references to the literature dating from 1901 to 1953, which are also covered by the main index. For example, picking on *Barkhausen noise* and the *Amplistat* as subjects not discussed in the text, one finds them indexed to pages 257 and 259 respectively, where the bibliography includes papers on these subjects. So comprehensive a survey deserves a place on the bookshelf of every designer or user of magnetic amplifiers.

D. A. B.

Wireless World Diary 1955

Pp. 79 of reference material and pp. 2 per week diary. Size 4½ in. by 3¼ in. Iliffe & Sons, Ltd., Dorset House, Stamford Street, London, S.E.1. Price 4s. 1d. (rexine), 5s. 10d. (Morocco leather), postage 2d. extra.

MEETINGS

I.E.E.

8th November. "Methods of Teaching Technical Writing", discussion to be opened by G. Parr, at 6 p.m.

10th November. "Standard Frequency Transmissions", by L. Essen, D.Sc., Ph.D. "The Standard Frequency Monitor at the National Physical Laboratory", by J. McA. Steele, B.Sc.(Eng.), and "Standard Frequency Equipment at Rugby Radio Station", by H. B. Law, B.Sc.(Tech.).

16th November. Celebration of the Jubilee of the Thermionic Valve. Opening Address by the Lord President of the Council, The Most Honourable the Marquess of Salibury, K.G., P.C., at 2.30 p.m., followed by "The Genesis of the Thermionic Valve", by Professor G. W. O. Howe, D.Sc., LL.D. "Thermionic Devices from the Development of the Triode up to 1939", by Sir Edward Appleton, G.B.E., K.C.B., M.A., D.Sc., LL.D., F.R.S., at 3.30 p.m. "Developments in Thermionic Devices since 1939", by J. Thomson, M.A., Ph.D., D.Sc., at 5.30 p.m.

22nd November. "Plastics for the Radio Engineer", by Maldwyn Jones.

23rd November. "The Application of the Hall Effect in a Semi-Conductor to the Measurement of Power in an Electromagnetic Field", by Professor H. E. M. Barlow, Ph.D., B.Sc.(Eng.), and "Audio-Frequency Power Measurements by Dynamometer Wattmeters", by A. H. M. Arnold, Ph.D., D.Eng.

30th November. "The Servicing of Electronic Measuring Instruments and its Effect on their Design", discussion to be opened by Denis Taylor, M.Sc., Ph.D.

1st December. "The Vertical Radiation Patterns of Medium-Wave Broadcasting Aerials", by H. Page, M.Sc., and G. D. Monteath, B.Sc.

6th December. "The Applications and Limitations of Electronic and other Computers", discussion to be opened by L. G. Brazier, Ph.D., B.Sc.

These meetings will be held at the Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2, and, except where otherwise stated, will commence at 5.30 p.m.

Brit.I.R.E.

24th November. "The Development and Design of Direct-Coupled Oscilloscopes for Industry and Research", by M. J. Goddard, to be held at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1, at 6.30 p.m.

The British Kinematograph Society

24th November. "Factors affecting Quality in Colour Television", by I. J. P. James, B.Sc., to be held at the Gaumont-British Theatre, Film House, Wardour Street, London, W.1, at 7.15 p.m.

STANDARD-FREQUENCY TRANSMISSIONS

(Communication from the National Physical Laboratory)

Values for September 1954

Date 1954 September	Frequency deviation from nominal: parts in 10^8		Lead of MSF impulses on GBR 1000 G.M.T. time signal in milliseconds
	MSF 60 kc/s 1429-1530 G.M.T.	Droitwich 200 kc/s 1030 G.M.T.	
1	− 0·8	+ 2	+ 67·6
2	NM	+ 2	+ 65·5
3	− 0·9	+ 2	+ 64·5
4	− 0·8	+ 2	NM
5	− 0·8	+ 3	NM
6	− 0·8	+ 2	+ 61·8
7	− 0·8	+ 3	NM
8	− 0·7	+ 3	+ 60·2
9	− 0·7	+ 3	+ 59·8
10	− 0·7	+ 3	+ 58·6
11	− 0·8	+ 4	NM
12	− 0·8	+ 4	NM
13	− 0·8	+ 4	+ 56·2
14	NM	+ 4	+ 55·6
15	− 0·8	+ 4	+ 54·5
16	− 0·7	+ 5	+ 54·6
17	− 0·7	+ 4	+ 52·5
18	− 0·7	+ 3	NM
19	− 0·7	+ 4	NM
20	− 0·7	+ 4	NM
21	− 0·7	+ 4	+ 50·5
22	− 0·8	+ 4	+ 48·3
23	− 0·8	+ 3	+ 47·0
24	− 0·7	+ 5	+ 45·0
25	− 0·7	+ 5	NM
26	− 0·8	+ 4	NM
27	− 0·8	+ 5	+ 42·8
28	− 0·8	+ 4	+ 40·7
29	− 0·7	+ 4	+ 39·3
30	− 0·7	+ 4	+ 37·8

The values are based on astronomical data available on 1st October 1954.
NM = Not Measured.

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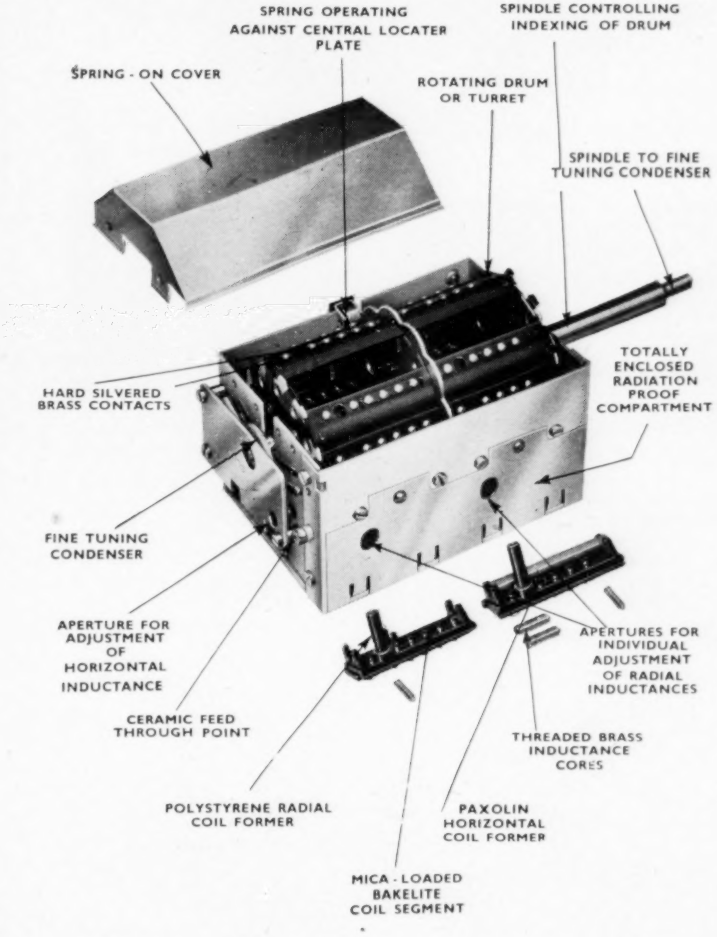
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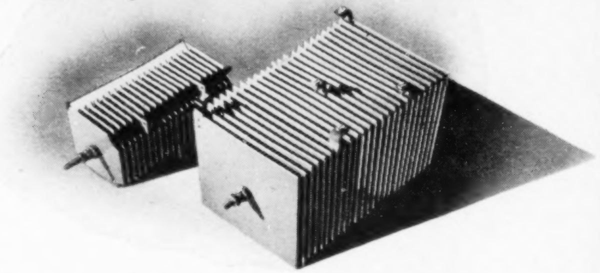

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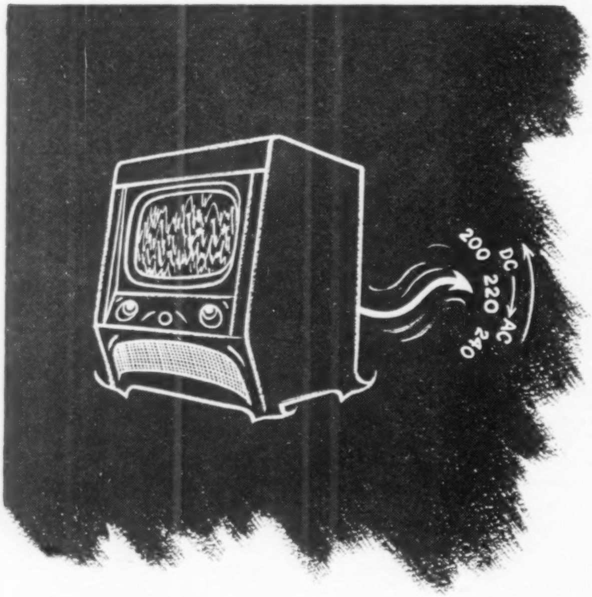

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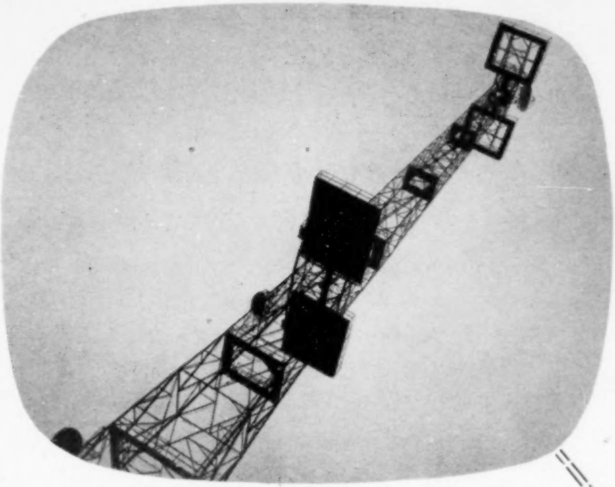

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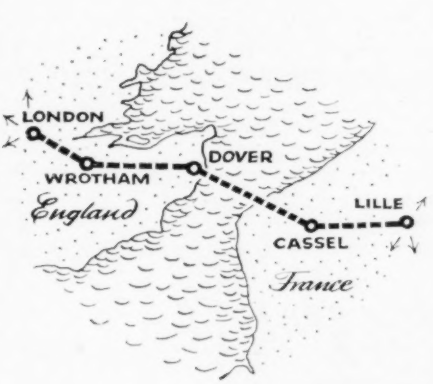

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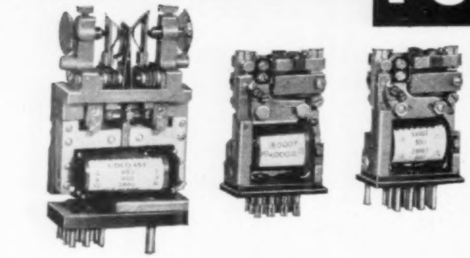

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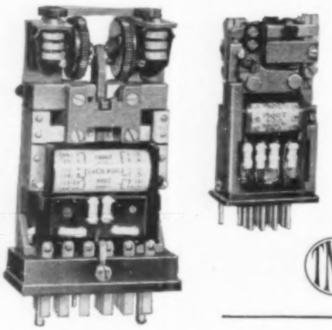

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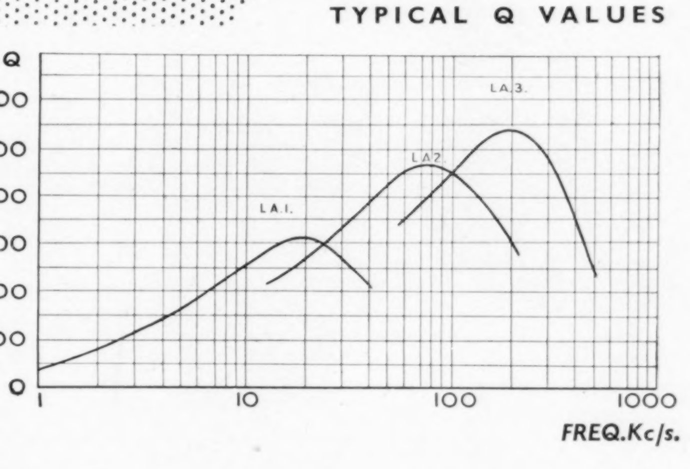

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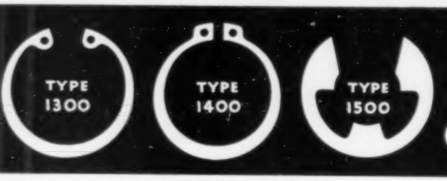

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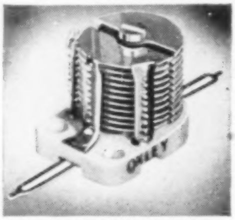

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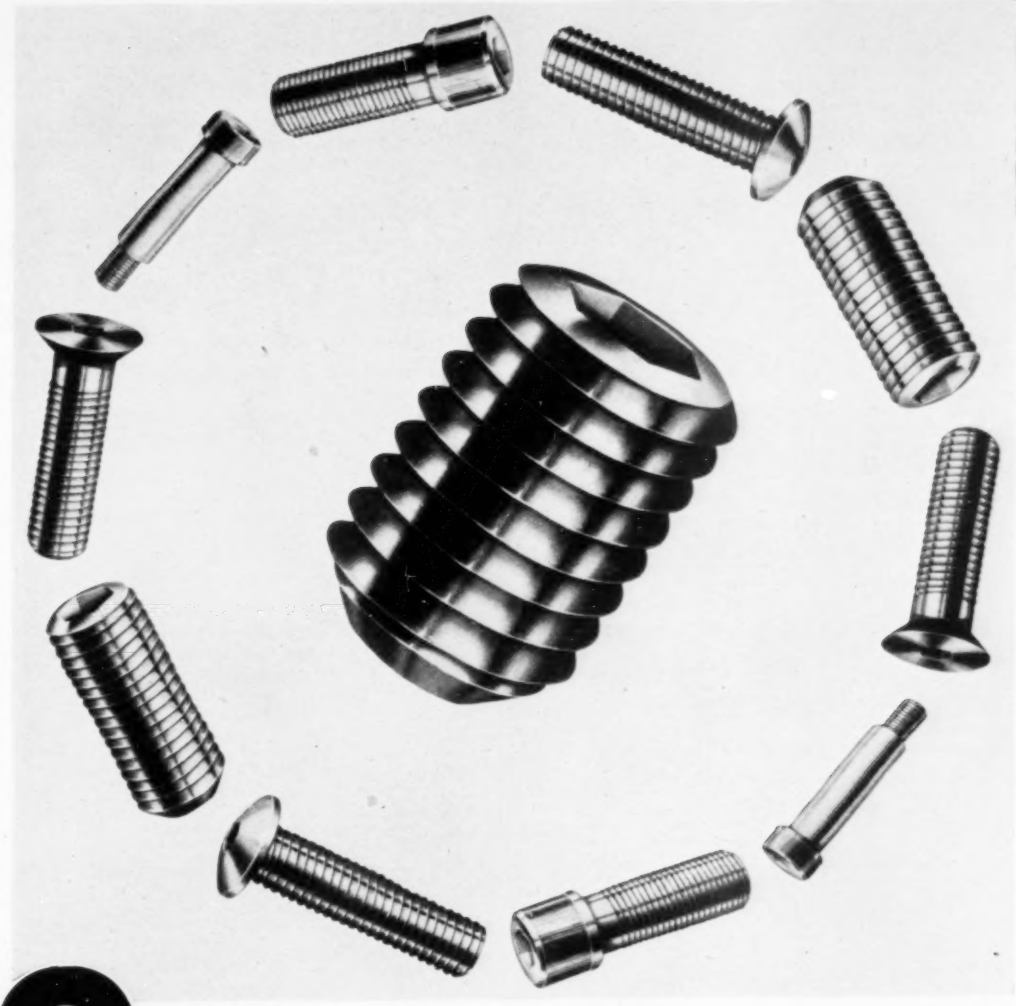

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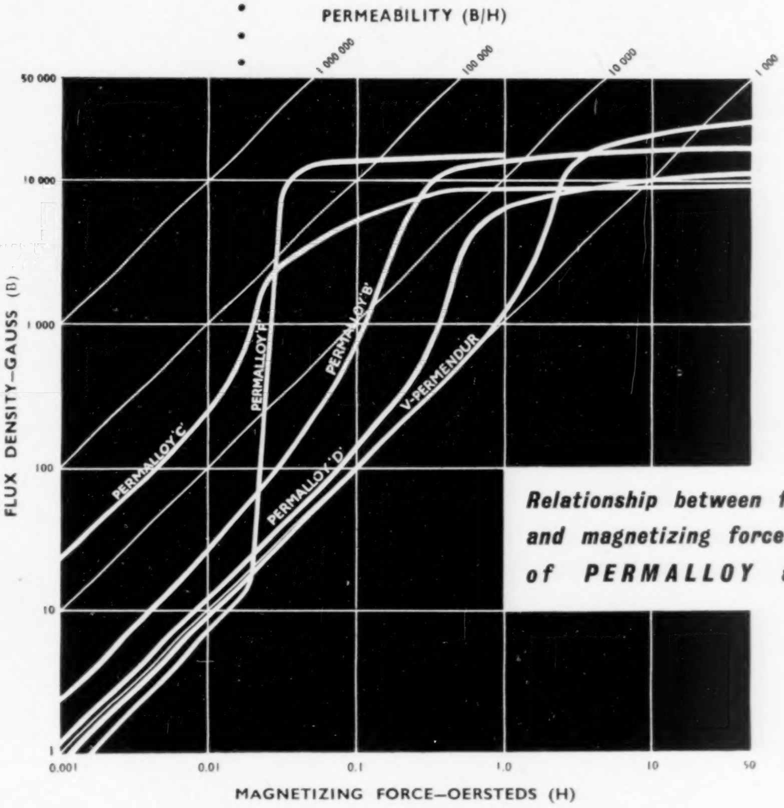

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exclusively specified

for the OSRAM 912

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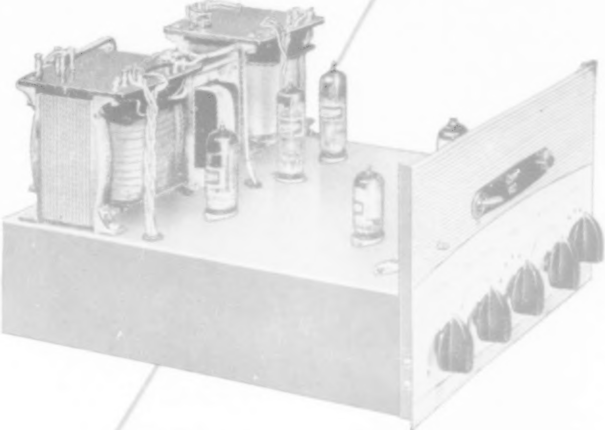

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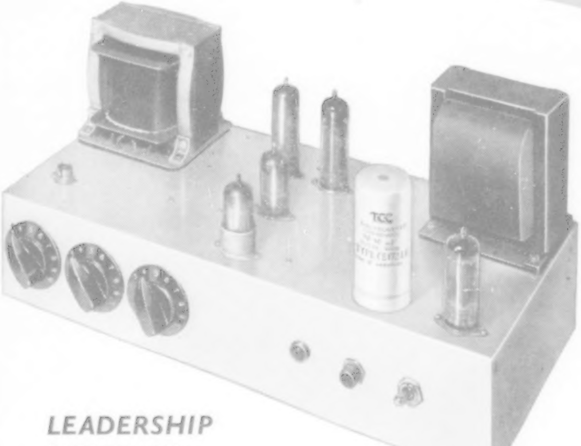

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1	270pF	±10%	SMP425	**1/5**
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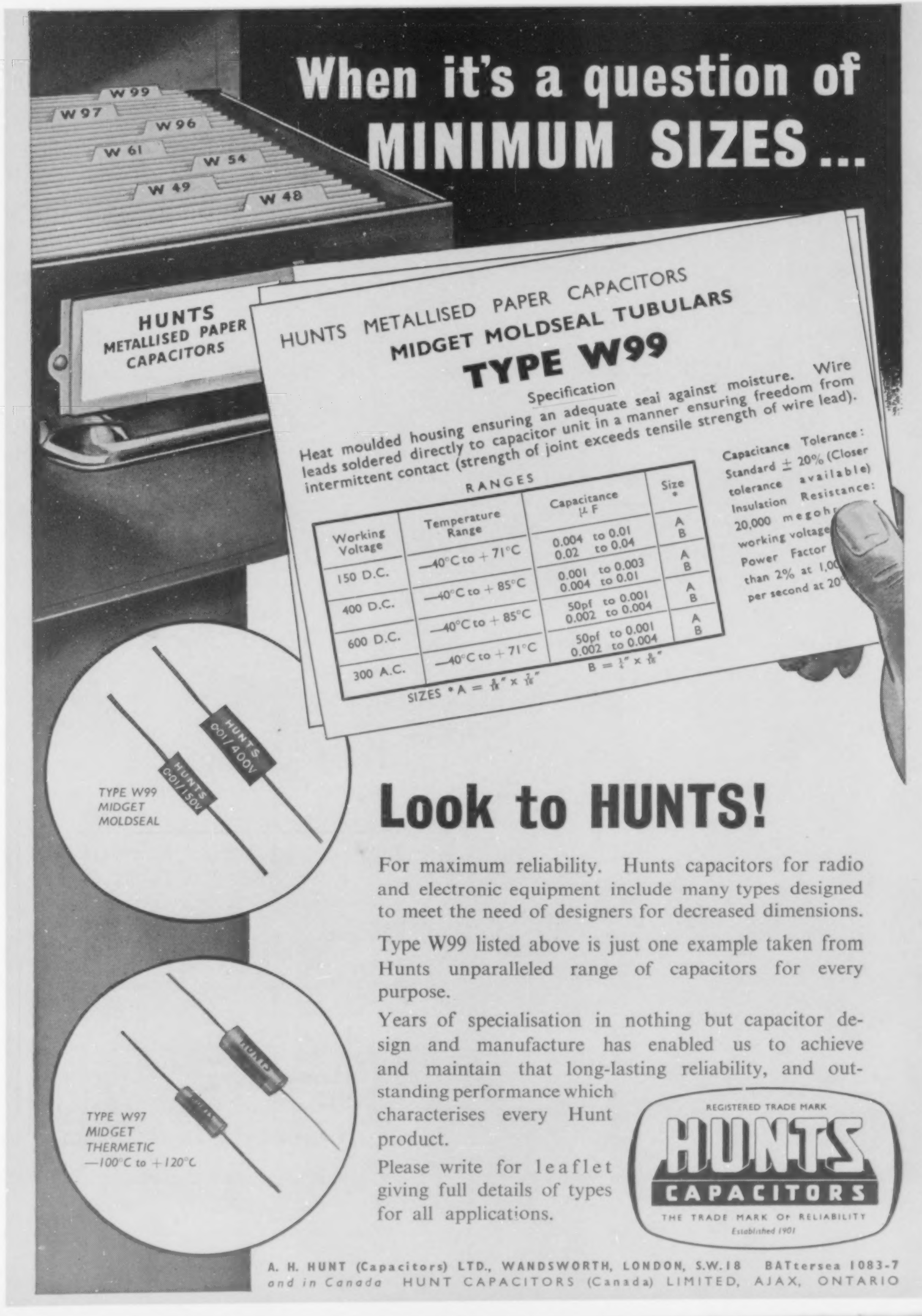

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600 D.C.	—40°C to + 85°C	50pf to 0.001 0.002 to 0.004	A B
300 A.C.	—40°C to + 71°C	50pf to 0.001 0.002 to 0.004	A B

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